Adapting to Climate Change
Canada’s First National Engineering Vulnerability Assessment of Public Infrastructure
April 2008
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Executive Summary

Canada’s engineers are on the front lines in helping ensure infrastructure adapts to the impacts of anticipated climate changes. Reliable studies, including those by the United Nations-backed Intergovernmental Panel on Climate Change, report statistical trends of global warming – evidenced by increasing global average air and ocean temperatures. These trends cast doubt on the validity of applying historic climate data when designing infrastructure. In the face of climatic changes, engineers may have to reconsider existing assumptions relative to infrastructure capacity and vulnerability.

Based on this concern, Engineers Canada conducted an engineering vulnerability assessment of the vulnerability of four categories of Canadian public infrastructure:

- stormwater and wastewater;
- water resources;
- roads and associated structures; and
- buildings.

While acknowledging that Canada’s inventory of public infrastructure extends far beyond the four selected categories, this work stressed the importance of initiating the process of assessing the engineering vulnerability of infrastructure to climate change. Moreover, examples of the four selected categories of public infrastructure are widely dispersed throughout Canada. This opened the way for selecting candidates for the seven infrastructure case studies that underpin this report. These infrastructure categories are also ones where the impact of climate changes may pose higher risks to public health and safety.

The work presented in this report was started in January 2007 and completed in March 2008. This report presents work completed to date. It is expected that further assessments, including of specific infrastructure systems, will follow from the findings, conclusions and recommendations of this report.

Engineering Vulnerability Assessment Protocol

The Engineering Vulnerability Assessment Protocol (the Protocol) is a pivotal outcome of this report. The five-step protocol provides a procedure for sifting through data for developing relevant information on specific elements of the climate and characteristics of a given infrastructure. The Protocol then considers how this information might interact and result in the infrastructure being vulnerable or adaptive to climate change.
Case Studies and Key Results

A number of components demonstrated high vulnerability to climate change in the case studies. These are listed below under each infrastructure category. More work is required to confirm the applicability of these conclusions to infrastructure located elsewhere in Canada.

Water Resources

Infrastructure selected for the water resources engineering vulnerability assessments case studies were:

- The City of Portage la Prairie (Manitoba) waterworks and related infrastructure;
- The Town of Placentia (Newfoundland and Labrador) including a breakwater, a floodwall, a building in a floodplain and a stretch of highway susceptible to flooding and washouts.

The following high vulnerability issues were noted as a result of the two case studies:

- Dam structures and seawalls in these locations may become more vulnerable to flooding.
- Intake structures, on the prairies in particular, may be vulnerable to drought conditions restricting feed-water supply to potable water treatment facilities.
- Intense winds, particularly tornado conditions, present a risk to a variety of infrastructure. In this case the probability of the event was generally determined to be very small. However, the consequence of the event was extreme.
- Ice storm events were determined to create a vulnerability to power supply systems putting the water resources infrastructure at risk.
- In Placentia, the most important risk factor was determined to be a combination of rising sea levels and storm surges. At the Public Infrastructure Engineering Vulnerability Committee Workshop, participants agreed that similar risks are being faced by most coastal infrastructure in Canada and recommended that the next series of engineering vulnerability assessments include studies of coastal infrastructure.

Stormwater and Wastewater

The case study selected in the stormwater and wastewater infrastructure category examined the Vancouver Sewage Area, located in Metro Vancouver, British Columbia. The study covered the collection system and the Iona Island Wastewater Treatment Plant.
The following high vulnerability issues were noted as a result of the Vancouver Sewage Area case study:

- In Metro Vancouver, sewer trunks, interceptors and sanitary mains are vulnerable to an increase in intense rain events.
- Common with the Placentia case study, coastal infrastructure is vulnerable to storm surges.

Roads and Associated Structures

The infrastructure systems selected for case studies of the roads and associated structures were located in the City of Greater Sudbury, Ontario, and in the City of Edmonton (Quesnell Bridge Refurbishment), Alberta.

The case studies found that these infrastructure systems were generally resilient to discrete, one-time, climate events. However, cumulative climate events could lead to vulnerability. The following high vulnerability issues were noted as a result of the two case studies:

- on the Quesnell Bridge, ice accretion and freeze-thaw cycles were found to create potentially significant vulnerabilities; and
- the most significant vulnerability observed for road systems in Sudbury resulted from a projected increase in heavy snow events. This had an impact on snow-removal procedures for sidewalks.

Buildings

Case studies of two sets of buildings infrastructure focused on thermosyphon foundations in northern Canada and on three Government of Canada buildings in Ottawa, Ontario.

The thermosyphon foundation study in the Northwest Territories was a unique application of the engineering vulnerability assessment methodology. The thermosyphon study focused on one infrastructure element over 10 different sites while the other case studies focused on multiple infrastructure elements in one location.

Consistent with other case studies, the thermosyphon case study identified that thermosyphon installations in the Northwest Territories are resilient, at least in the short term, to increasing air temperatures provided that other infrastructure deficit issues are managed. Issues that resonated within the case study included:

- design;
- installation;
- ongoing maintenance;
- monitoring the temperature of the thermosyphon foundation over time; and
- monitoring other physical changes at the thermosyphon location that may compromise the performance of the thermosyphon foundation.
The following high vulnerability issues were noted as a result of the Ottawa buildings case study:

- buildings in Ottawa are demonstrating high vulnerability to changes in snow and wind events; and
- cooling systems may be highly vulnerable to changes in humidity.

Conclusions

A central finding from the first National Engineering Assessment of the Vulnerability of Public Infrastructure to Climate Change is that the Engineering Protocol for Climate Change Infrastructure Vulnerability Assessment works.

In its general conclusions and recommendations, this work also draws attention to the interdependence of infrastructure in Canada. Generally, that infrastructure is designed to withstand extreme events. However, that does not mean the impact of climate change can be ignored.

The conclusions from this study break out into seven themes.

Theme 1: Some infrastructure components have high engineering vulnerability to climate change.
In the case studies a number of components demonstrated high vulnerability to climate change. More work is required to confirm the applicability of these conclusions to infrastructure located elsewhere in Canada.

Theme 2: Improved tools are required to guide professional judgment.
Better consensus is needed regarding the definition of what is considered critical loss of infrastructure as well as what constitutes a catastrophic failure. These definitions are needed for each of the four infrastructure categories assessed in this work.

Theme 3: Infrastructure data gaps are an engineering vulnerability.
Many of the case studies reported significant gaps in the availability of infrastructure data. Thus engineers, operators and decision-makers have no clear definition of the capacity and resiliency of the system. These data gaps contribute to the overall vulnerability of infrastructure.

Theme 4: Improvement is needed for climate data and climate change projections used for engineering vulnerability assessment and design of infrastructure.
The seven case studies revealed significant gaps in the types and nature of historical climate data needed to conduct engineering vulnerability assessments. The historical data establishes the baseline to compare future changes derived from the climate change projection models.

Theme 5: Improvements are needed in design approaches.
There is a need to systematically document the climatic data that has been used to establish climatic design values in existing codes and standards in the four infrastructure categories.

It is much easier to apply results of an engineering vulnerability assessment during design than to existing, mature facilities. It is important to apply assessment of climate change vulnerability to new technologies, many of which have unknown performance capabilities relative to the effects of climate change on infrastructure.
Theme 6: Climate change is one factor that diminishes resiliency.
In recent years, concerns have been raised in Canada about present level of maintenance and future needs for infrastructure. Factors affecting the resiliency of infrastructure may include the age of the asset; level of maintenance and monitoring of facilities; changes in populations; and the amount of use the infrastructure receives. Climate change is likely to intensify the engineering vulnerability if current levels of maintenance continue. Properly maintained infrastructure enables the infrastructure and its components to function as designed, which includes accounting for changing climate events. A holistic approach is needed to deal with the issue, including consideration of financial managerial and social factors as well as climate change.

Theme 7: Engineering vulnerability assessment requires multi-disciplinary teams.
Assessment of vulnerability to climate change requires interdisciplinary approaches involving a range of expertise, including, but not limited to, engineers, climatologists, architects, hydrologists and others. Ideas on the vulnerability of a piece of infrastructure many differ between engineers and managers, on the one hand, and, personnel involved in day-to-day hands-on operation of infrastructure on the other.

Recommendations
Five recommendations arise from the work completed to date:

Recommendation 1: Revise and update the engineering vulnerability assessment protocol
During the execution of the case studies, a number of minor issues were identified with the current version of the Engineering Vulnerability Assessment Protocol (Rev 7.1, 31 Oct. 2007).

Recommendation 2: Conduct additional work to further characterize the vulnerability of Canadian public infrastructure to climate change
There is a need to conduct further engineering vulnerability assessments to more fully characterize the vulnerability of Canadian public infrastructure to climate change.

Recommendation 3: Develop an electronic database of infrastructure vulnerability assessment results
The analysis provided in this report is based on analyzing limited data. As more information accumulates, an electronic database will significantly aid in the analysis of vulnerability trends within a category of infrastructure, regionally and/or nationally.

Recommendation 4: Assess the need for changes to standard engineering practices to account for adaptation to climate change
Some of the case studies determined that the current design codes and practices applicable to the infrastructure under consideration could be improved. In some cases, this was related to dated information used within a standard and in others it was based on the view that climate change should be factored into new designs. In light of this experience, further work is needed to:

- review codes and standards applicable to the four categories of infrastructure that are the current focus of the Public Infrastructure Engineering Vulnerability Committee and determine specifically where dated climatic information is used;
• maintain a dialogue between engineers, scientists, modellers and climatologists to clarify the climate data needs and formats to support the design and management of engineering;
• maintain a dialogue with codes and standards organizations to communicate the outcomes from this engineering vulnerability assessment in order to evaluate the need to update codes and standards; and
• investigate incorporating the use of the Engineering Protocol for Climate Change Infrastructure Engineering Vulnerability Assessment, or similar assessment processes, into design processes for new infrastructure and major infrastructure rehabilitation in Canada.

**Recommendation 5: Initiate an education and outreach program to share learnings from this assessment with practitioners and decision-makers**

Public infrastructure systems do not function in total isolation. Multiple stakeholders have a role to play in ensuring robust and resilient public infrastructure for assurance of serviceability and public safety. Key learnings from this initiative should be shared with other constituencies in order to promote effective infrastructure design, operation and management.
1 Introduction

Much of the time Canadians are in, on or surrounded by infrastructure. It may be roadways, ports, buildings or sometimes the less-visible water and wastewater systems that service communities. Remote areas of the country have infrastructure, such as airstrips and possibly pipelines. Even where nothing is visible, telecommunications infrastructure connects Canadians over vast distances.

Historically, the dwellings of First Nations can be considered Canada’s first infrastructure. Rivers and forts provided infrastructure during the era of the fur trade. In terms of nation-building, the 19th century construction of the Canadian Pacific Railway likely represents our most important piece of infrastructure. Over time, the design of infrastructure has evolved and adapted to meet changing circumstances. Canada’s professional engineers have played a key role in that process and in adapting to change.

Canadians, and indeed the global population, are now facing the prospect of climatic changes unprecedented in recorded human history. Over recent decades, much debate has focused on the causes of that change – whether it results from human activity or arises due to natural cyclical changes. While discussion may continue over the basis for the change, there is mounting evidence that our climates and weather patterns are changing. This begs questions about how we will deal with such changes. As the people responsible for designing and overseeing the ongoing operation and integrity of much of Canada’s infrastructure, professional engineers have an ethical responsibility of ensuring that our infrastructure remains safe and serviceable in the face of climate change.

1.1 Engineers, Climate Change and Infrastructure

Engineers Canada is the national organization of the 12 provincial and territorial associations and ordre that regulate the practice of engineering in Canada and license the country’s more than 160,000 professional engineers. Throughout Canada, thousands of professional engineers fill key design, maintenance, operational and regulatory roles in connection with roads, buildings, water systems and a wide range of other public infrastructure.

Infrastructure is closely linked to climate and weather. Canada’s great seasonal swings in weather and the wide variety of climatic conditions are taken into account in design standards for public infrastructure. Those who design, construct, maintain and operate our infrastructure also take into account climatic and weather information in ensuring the safety and reliability of facilities.

Traditionally, for infrastructure design and operational decisions, historic weather statistics have served as dependable sources of information. However, there is mounting evidence, including from the United Nations-backed Intergovernmental Panel on Climate Change, that warming of the climate is unequivocal as shown by changing statistics. It is evidenced by increases in the global average air and ocean temperatures, widespread melting of snow and ice, and a rising global average sea level.
In the face of such evidence of climate change, doubts are cast upon the validity of using historic data and premises applied to infrastructure design. Existing facilities, some possibly built using now-outdated assumptions, may not have sufficient resiliency to future climate change impacts. Added demands arising from changing climatic conditions could mean that, given their life span, some infrastructure lack the necessary load capacity or adaptive capability. Shortfalls of this kind could leave some of Canada's infrastructure vulnerable and ill-prepared to cope with adverse climate effects, including variable and extreme weather events. The degree of vulnerability may relate to:

- the character, magnitude and rate of change in climate conditions;
- the sensitivities of infrastructure to the changes; and
- the built-in capacity of infrastructure to absorb predicted changes.

Professional engineers, along with government decision-makers and others responsible for public safety and effective operation of public infrastructure, need to identify such vulnerabilities and, when appropriate, recommend corrective actions.

1.2 Scope of Report

This report presents the results from seven case studies of infrastructure that have been completed under the framework of a national engineering vulnerability assessment of Canada's public infrastructure. The national assessment involves a systematic evaluation of the engineering vulnerabilities of different categories of infrastructure located in various climatic and geological areas in the country. It is necessarily limited to public infrastructure that is owned, operated and governed by the three levels of government in Canada.

The diversity and range of infrastructures that may be vulnerable to climate change is enormous. With limited resources and time, it was necessary to focus on a few categories that provide key public services. The categories selected included:

- water resource systems, particularly potable-water collection and treatment systems, and coastal flood-control systems;
- stormwater and wastewater collection and treatment systems;
- roads and associated structures, particularly bridges; and
- buildings.

Disruption or damage to these widespread and common categories of physical infrastructure could have major ramifications for public health, safety and effective functioning.

It is stressed that this is a progress report, not a definitive or final national assessment. It is a compilation of the case study reports completed to date with preliminary conclusions on potential vulnerabilities by infrastructure category. Recommendations for further work conclude the work to date.
More work in the form of additional case studies is needed to make the results representative of the infrastructure in all regions in the country. However, this report, its conclusions and recommendations provide a solid foundation to conduct additional engineering vulnerability assessments at the local level and to plan similar assessments for other categories of public infrastructure.

The seven case studies were completed in partnership with host partners that own and operate the infrastructure that was assessed. The case studies were completed by engineering consultants contracted by the local partner under a co-funding arrangement between the host and the project. The consultant reports from the individual case studies represent the major milestone/deliverable at this stage of the process. They provide examples of completed assessments in each of the four selected infrastructure categories in various regions of Canada. The case studies can serve as templates for future case studies in other locations and with other partners.

Case studies entailed securing volunteer communities to serve as hosts for the assessments. In the selection process, every effort was made to choose at least one case study for each category of infrastructure and to provide as much geographic coverage as possible.

## 2 Background

Working with other interested parties, Engineers Canada formed the Public Infrastructure Engineering Vulnerability Committee (the Vulnerability Committee) in August 2005. In its first year of operation, the committee focused its efforts on:

- defining the terms of reference for the assessment work; and
- planning a feasible methodology and process for a project to execute the assessment.

The work presented in this report was started in January 2007 and completed in March 2008.

The Vulnerability Committee serves as a steering committee to facilitate and oversee the broad-based national engineering assessment of infrastructure and climate change, which besides being a Canadian “first”, in terms of its aims and scope, also leads the way internationally. Efforts coordinated through the Vulnerability Committee have led to the publication of this report.

### 2.1 Definitions

The following defines some key terms used in this report;

**Climate Change** (as defined by the Intergovernmental Panel on Climate Change) refers to a change in the state of the climate that can be identified (e.g., using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to variability or as a result of human activity.
National Engineering Vulnerability Assessment involves a process initiated in 2005 to gather information and apply engineering judgement on the vulnerability of Canadian public infrastructure to projected climate change. The assessment led to the preparation of this report and its recommendations.

Public Infrastructure consists of those facilities, networks and assets operated for the collective public benefit – including the health, safety, cultural or economic well-being of Canadians – by government and/or non-government agencies.

Engineering Vulnerability is defined as the shortfall in the ability of public infrastructure to absorb the negative effects, and benefit from the positive effects, of changes in the climate conditions used to design and operate infrastructure. Engineering Vulnerability is a function of:

- character, magnitude and rate of change in the climatic conditions to which infrastructure is predicted to be exposed;
- sensitivities of infrastructure to the changes, in terms of positive or negative consequences of changes in applicable climatic conditions; and
- built-in capacity of infrastructure to absorb any net negative consequences from the predicted changes in climatic conditions.

Adaptive Capacity is the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.

Design Life is the expected service life intended by the designer.

Service Life is the period of time after installation during which an infrastructure or its component parts meet or exceed performance requirements.

2.2 The Public Infrastructure Engineering Vulnerability Committee

The membership of the Public Infrastructure Engineering Vulnerability Committee (Vulnerability Committee) consists of senior representatives of the engineering profession; federal, provincial, territorial and municipal governments; plus other key stakeholders interested in climatic changes that impact infrastructure. The Vulnerability Committee has balanced regional and sectoral representation. A detailed listing of organizations, departments and agencies represented on the Vulnerability Committee is presented in Appendix F.

Formation of this steering committee, in 2005, stemmed from the need of the engineering profession and other interested parties to better understand how climate changes may affect the design, construction and operation of public infrastructure in Canada. The Vulnerability Committee’s objectives are:

- to develop the terms of reference for a national assessment of the vulnerability of public infrastructure to the impacts of climate change and to oversee the execution of the project;
- to set up and manage the infrastructure expert working groups and report on their work as required;
• to review the recommendations from the infrastructure expert working groups and advise on responses and follow-on work that is required;
• to facilitate the development and/or inclusion of specific best engineering practices that adapt to climate change impacts in appropriate documentation.

2.3 The Four Categories of Infrastructure

Drawing on engineering and scientific expertise, the Vulnerability Committee selected the following four categories of infrastructure as initial candidates for engineering vulnerability assessment:

- water resources;
- stormwater and wastewater;
- roads and associated structures; and
- buildings.

These four categories were selected for the first series of engineering vulnerability assessments because these infrastructure systems are common across all of Canada. Furthermore, they were chosen because the highest immediate risk to public health and safety arising from climate change impacts are posed within these categories of infrastructure.

Infrastructure is a wide-ranging concept and each of the four categories selected for vulnerability assessment as part of the current report generally include numerous subcategories (for example, buildings would cover schools, hospitals and other structures). As noted, this vulnerability-assessment process focuses on “public” infrastructure, a term that covers a great variety of physical facilities, networks and assets. Typically, public infrastructure is operated by government and/or non-government agencies for collective public benefits – including health, safety, social and/or economic benefits. In 2002, government-owned engineering infrastructure in Canada was valued at $154.8 billion. That included close to one million kilometres of roadways and about 56,000 bridges. The totals continue to increase and are even larger if “public” infrastructure is extended beyond that owned by governments.

By no means do the four infrastructure categories selected for initial assessment reflect the entire spectrum of public infrastructure in Canada. Electrical transmission systems, pipelines and airports are just a few forms of infrastructure not covered by the current assessment. Examples of the four selected infrastructure categories are widely distributed throughout the country. This increases the likelihood that those responsible for similar infrastructure are also giving thought to comparable vulnerability assessments of their facilities. A wide selection of facilities in a given category also expands the potential pool of case study candidates.

While acknowledging the assessment has gaps, the Vulnerability Committee determined that it was important to launch the process and to test and validate the proposed engineering assessment protocol by evaluating the four chosen categories of public infrastructure. To do this, the Vulnerability Committee utilized the insight and expertise of four expert working groups established in each of the four infrastructure categories that define the scope of this assessment.
3 Methodology

3.1 Scoping Study

A scoping study was conducted as a first step. It resulted in recommendations on how best to proceed with the First National Engineering Assessment of the Vulnerability of Public Infrastructure to Climate Change. Three key recommendations emerged from the scoping study:

- develop an engineering protocol for climate change infrastructure vulnerability assessment;
- carry out a pilot study; and
- conduct case studies for various infrastructure categories in various areas of the country.

3.2 The Protocol

The assessments were conducted using the Engineering Vulnerability Assessment Protocol (the Protocol) developed during the course of this project and refined through its use in the seven case studies. Another key outcome for the national assessment project to date is the development and validation of the Protocol and the process to use it in engineering vulnerability assessment of a local or community infrastructure. The Protocol includes the use of climate-change scenarios as a key input to the engineering vulnerability assessment.

The key elements of the Protocol are discussed in Section 4.

Discussion on the use and application of climate change scenarios in such assessments is presented in Section 5.

3.3 Pilot Study

The Engineering Vulnerability Assessment Protocol was “test-driven” by subjecting the City of Portage la Prairie, Manitoba’s water-works system and the drinking-water treatment plant to a pilot study engineering vulnerability assessment. This field test helped refine the parameters, methods and approaches used in the Protocol.
3.4 Case Studies

The Engineering Vulnerability Assessment Protocol, with refinements arising from the Portage la Prairie pilot study, was then applied in a series of six additional case studies focusing on the four infrastructure categories selected for initial assessment. Besides representing different categories of infrastructure, the settings of the case studies were widely dispersed geographically – from British Columbia to Newfoundland and into the North. This provided opportunities to apply the Protocol within differing climatic conditions and to various geographical characteristics (such as soil, vegetation and topography) that will also render the infrastructure more or less vulnerable (for example, melting permafrost on bedrock versus clay soil).

Recommendations stemming from individual case studies may also apply to other similar infrastructure. Certain findings may have general applicability to different categories of infrastructure.

3.5 National Workshop

The Vulnerability Committee convened the National Workshop on Engineering Vulnerability to Climate Change in Ottawa in March 2008. Workshop participants reviewed the results from the Canada-wide assessment and the case studies. The workshop provided an opportunity to consolidate and fine tune the recommendations included in this report.

3.6 Engineering Vulnerability Assessment

This report outlines the key vulnerabilities identified for each infrastructure assessed in the seven case studies. Results are tabulated in a matrix format that shows both the climate factors and specific infrastructure elements that have been found to be vulnerable to climate change in the case studies. The tables are high-level summaries and, where applicable, consolidate the results from multiple case studies. Over time, with additional case studies, this approach will provide engineers and decision-makers with a useful tool to conduct preliminary screening analysis on their particular infrastructure. Vulnerabilities that have been identified in earlier case studies may exist on specific infrastructure being considered as part of a future engineering vulnerability assessment.

As engineering vulnerability assessments are expanded into other categories of infrastructure, similar consolidated matrices also will be constructed for those categories.

In the seven case studies, and in this report, a clear distinction is made between vulnerability and engineering vulnerability. In the broadest sense, vulnerability includes a wide range of factors that may affect the resiliency of a system, including:

- engineering considerations;
- political decision-making;
- socio-economic factors; and
- the risk tolerances of the affected populations and stakeholders and how this motivates political processes.
Engineering vulnerability is one important element that must be clearly understood in order to fully address the other factors that affect vulnerability.

This engineering vulnerability assessment focuses primarily on engineering considerations and asks if the infrastructure analyzed would continue to perform its design function given the climate change stresses being considered. The alternative means to handle the loss of infrastructure functionality are not addressed. Rather, the focus is on identifying circumstances where the infrastructure system ceases to operate as designed.

In an engineering vulnerability assessment, infrastructure is characterized based on its relevant subcomponents (elements). These elements are evaluated against projected climate change events and the performance response of the infrastructure is assessed. The factors (elements, performance response and climate) that are deemed to be important vary based on the infrastructure type and its location. As a first step, practitioners must use professional judgement to determine which factors will be used in the engineering assessment. In considering which factors are relevant, practitioners may often review the factors used in other assessments. Not all factors considered in the previous case studies may be relevant and there may be factors that were not considered in the previous work that are important to the case at hand. Once again, professional judgement must be used to make these determinations. The following sections also identify the factors considered in the case studies commissioned in connection with this report.

The seven case studies conducted for this report did not focus on events, external to the infrastructure, that may lead to adverse impacts on the infrastructure. This was occasionally identified and evaluated in the form of potential cascading events, but was not the primary focus of the case studies. This may be an element in future vulnerability assessment case studies.

### 3.7 Sampling Strategy

In support of a sound sampling strategy for future vulnerability assessments, the Vulnerability Committee sponsored the development of a matrix approach to identify priority infrastructure and locations for future case studies. This resulted in a three-step approach that promotes the identification of:

- the infrastructure of interest for assessment;
- what climate change influences are expected to impact this infrastructure; and
- where in the country these climate change influences are expected to occur.

This strategy was developed in parallel with the current set of case studies that forms the basis for this report. The Vulnerability Committee has adopted this method as part of the selection process for future case studies.

The report outlining the development of the sampling matrices and their application is presented in Appendix D.
The Engineering Vulnerability Assessment Protocol

The Engineering Vulnerability Assessment Protocol (the Protocol) provides a procedure or template for sifting through data to develop relevant information on:

a) specific elements of the climate;

b) characteristics of a given infrastructure; and

c) how a) and b) might interact to make that infrastructure vulnerable (or resilient) to climate change.

The five-step Protocol supplies a guide for practitioners to follow while conducting a climate change infrastructure engineering vulnerability assessment on specific infrastructure. It can assist practitioners to effectively incorporate climate change adaptation into design development and management decision-making. The first part of the Protocol helps the practitioner identify key information needed to conduct the assessment. The Protocol goes on to direct the practitioner on ways to continuously evaluate the quality and availability of data needed to support conclusions and recommendations related to climate changes and their impact on the specific infrastructure.

The Protocol utilizes the following five steps as indicated in Figure 2.

![Diagram of Relevant Interaction between Climate and Infrastructure](image)
**Step 1: Project Definition**
Step 1 in using the Protocol centres on defining the boundary conditions of the vulnerability assessment by describing the infrastructure being assessed, its location, load, age and other relevant factors, plus the historic climate of the region where the infrastructure is located. Step 1 also involves identifying major documents and information likely to be relevant to the assessment.

**Step 2: Data Gathering and Sufficiency**
Step 2 calls upon interdisciplinary judgement in the form of engineering, climatology, operations, maintenance and management expertise to be applied to the following two key activities.

1) Specifying components of the infrastructure to be considered in the assessment

   This involves identifying the infrastructure’s physical components (and how many); location; technical considerations (e.g., construction material, age, regional importance and physical condition); operation and maintenance practices; and performance measures to operate and manage the infrastructures (e.g., policies, guidelines, regulations, as well as insurance and legal considerations).
2) Identifying sources of climate information

Sources include historical climate data from Environment Canada as well as local or regional climate data collected by the province or at the municipal level. Other useful sources include the National Building Code of Canada, Appendix C, Climate Information; flood-plan mapping; regionally specific climate modelling; heat units (e.g., for energy use, HVAC, agriculture and degree-day) plus other appropriate resources such as regional or local studies completed for the area of interest. Together, such information sources contribute toward understanding of how climate variables – including increases or decreases in temperature, more or less precipitation, or the timing and intensity of weather events – may impact infrastructure.

**Step 3: Vulnerability Assessment**

In Step 3, information gathered during the earlier steps is used to identify relationships between the infrastructure components, the climate and other factors that could lead to infrastructure vulnerability. This requires identifying components of the infrastructure susceptible to climate changes and then relating these vulnerable components to other aspects of the infrastructure. Depending on the number of relationships involved, Step 3 anticipates that the practitioner conducting the assessment will prioritize these relationships.

Using this information, the practitioner applies professional judgement and works with the facility’s owner and operational personnel to assess the infrastructure’s vulnerability and to identify areas in need of further evaluation or immediate action.

Step 3 also places an onus on the practitioner to identify and make recommendations on infrastructure or components of it not rendered vulnerable by climate changes.

**Step 4: Indicator Analysis**

Building on the previous step, Step 4 anticipates that the practitioner will conduct vulnerability indicator analysis. This analysis would consider the current load on the infrastructures, climate change and other effects on the infrastructure. It would also take into account the infrastructure’s capacity as it ages and as changes in capacity occur.

This will allow the practitioner to determine whether:

- a vulnerability exists – meaning total load exceeds total capacity; or
- an adaptive capacity exists – meaning total load is less than total capacity.

Under Step 4, if the results of the indicator analysis are brought into question by the quality of the data or by statistical error, the practitioner must reconsider the information gathered during Steps 1 and 2, and call for additional work outside the scope of the vulnerability assessment.

**Step 5 – Recommendations**

Based on Steps 1 through 4, recommendations in Step 5 generally will fall into the following categories:

- remedial action is required to upgrade the infrastructure;
- management action is required to account for changes in the infrastructure capacity;
- continued monitoring of performance of infrastructure and re-evaluation at a later time;
- no further action is required; and/or
- identification of gaps in data availability or data quality that require further work.
5 Climate Models for Engineering Vulnerability Assessment

Projections of climate change are derived from climate-modelling experiments. Climate models are mathematical models that simulate the climate system's behaviour based on the fundamental laws of physics. They are the primary tools used to assess future climate conditions and provide the virtual meteorological data that feeds into the construction of climate scenarios. Although models are the best available representations of the planet, they remain a simplified version of the climate processes.

Global climate models simulate planet-wide climate dynamics at a coarse spatial resolution. (More than 20 global climate models have been run multiple times on several greenhouse-gas scenarios.) Indeed, each grid of the model has a horizontal resolution of approximately 350 km. Since the spatial resolution of the global climate models is not high enough to study regional or local effects of future climate change, downscaling techniques, using dynamical or statistical methods, have been developed to get more detail at regional or local scales.

Statistical downscaling serves to develop detailed local climate scenarios based on output from global climate models. It does so by constructing empirical statistical links between large-scale results and local conditions. It involves the analysis of local-scale observed variables and large-scale atmospheric variables, establishing derived relationships between the two and applying them to global climate model output. The assumption at the base of this analysis is that the current relationships between the two variables will also be valid in future climate conditions.

Dynamical downscaling consists of downscaling from global scales to regional or more local scales using regional climate models by applying a coupled atmosphere-land surface model to a limited area of the globe. Horizontal scales are typically approximately tens of kilometres, giving them a much higher resolution than global climate models. Since regional climate models are based on fundamental laws of physics, they include the full range of physical processes that interact and affect the climate. The physical processes are based on the same types as those described in the global climate models for every grid square included in its domain. They therefore have the ability to provide a wider array of variables than statistical downscaling techniques and are not dependent on observed values.

The high resolution of regional climate models provides results at spatial scales that apply more closely to regional and local community needs for vulnerability and impacts assessments. For
example, the Canadian Regional Climate Model, the one developed and used by OURANOS, a research and development consortium specialized in climate change, to produce climate scenarios for the Public Infrastructure Engineering Vulnerability Committee case studies presented in this report, has a horizontal grid size in the order of 45 km. The main inconvenience of regional climate models is that they are computationally demanding, placing constraints on the domain size, number of experiments and duration of simulations that can be conducted. A variety of methods and tools are being developed and continue to be improved to increase the resolution of the regional climate models. Work towards improving these models will better identify uncertainties associated with the results (for both long-term trends and extreme weather event statistics) and become increasingly useful for local scale assessments of anticipated climate change impacts.

5.1 Climatic Parameters for the Engineering Vulnerability Assessment

The Canadian Regional Climate Model, with a 45-kilometre grid size, was used by OURANOS, to produce future climate scenarios that provide projections of certain climatic parameters to support the seven case studies that have been completed to date. Three 30-year time horizons, centered on the following decades, were selected for future projections:

1) 2020s (2011-2040)
2) 2050s (2041-2070)
3) 2080s (2071-2100)

These time periods were selected to provide insight into changes in climatic parameters over this century and to be representative of future time frames for planning infrastructure design or rehabilitation cycles. Aside from the Portage la Prairie pilot study, the case studies did not examine the last timeframe. It is well in excess of most existing infrastructure service life as well as beyond the service life of most new infrastructure being designed in 2008. Future vulnerability assessments should tie their climate change projection needs to time frames that match the design or remaining service life of existing infrastructure or the service life for new infrastructure.

Each case study requested climate change scenarios in accordance with an order form that included a list of relevant climatic factors that were specified by the consultant performing the assessment. The list of climatic elements and potential change factors that were used as the master list for all four infrastructure categories is presented in Table 1.
Generally, most data necessary for the vulnerability assessments is available and scenarios of climate change are possible for almost all climate indicators. However, the quality or usefulness of the data (both observed and predicted) varies greatly. Often, observed data is available, provided there are weather stations present to capture the event and a sufficient density of stations in a given area to establish the extent of the event. As a result, scenarios are available but the level of confidence in the data varies. Table 1 also provides an assessment of the availability of climate data and the confidence level of the associated climate change scenarios.

Table 1: Climate Elements and Potential Change Factors Considered in Case Studies

<table>
<thead>
<tr>
<th>Climatic Elements</th>
<th>Potential Change Factor</th>
<th>Historic Data</th>
<th>Climate Change Scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>(2020s, 2050s, 2080s)</td>
</tr>
<tr>
<td>Temperature</td>
<td>Rate of change</td>
<td>a</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Mean values</td>
<td>a</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Extremes</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>High summer</td>
<td>a</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Low winter</td>
<td>a</td>
<td>2</td>
</tr>
<tr>
<td>Precipitation as rain</td>
<td>Frequency</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>One-day</td>
<td>a</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Less than 24 hours (short duration)</td>
<td>b</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Multi-day</td>
<td>a</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Total annual</td>
<td>a</td>
<td>2</td>
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<tr>
<td></td>
<td>Total seasonal</td>
<td>a</td>
<td>2</td>
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<tr>
<td></td>
<td>Intensity of rain events</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>One-day</td>
<td>b</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Less than 24 hours (short duration)</td>
<td>b</td>
<td>3</td>
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<tr>
<td></td>
<td>Proportion of annual precipitation as rainfall</td>
<td>a</td>
<td>2</td>
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<tr>
<td></td>
<td>Proportion of seasonal precipitation as rainfall</td>
<td>a</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Drought conditions</td>
<td>a</td>
<td>2</td>
</tr>
</tbody>
</table>
| Climatic Elements          | Potential Change Factor                          | Historic Data¹ | Climate Change Scenarios²  
<table>
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<tr>
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<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Frequency</td>
<td>a</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Total annual precipitation</td>
<td>a</td>
<td>2</td>
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<tr>
<td></td>
<td>Total seasonal precipitation</td>
<td>a</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Magnitude of snow events</td>
<td>a</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Frequency and intensity of rapid snow melt events⁴</td>
<td>c</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Rain on snow events</td>
<td>a</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Mean values (one-hour mean winds)</td>
<td>b</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Monthly</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Seasonal</td>
<td>b</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Annual</td>
<td>b</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Extreme/gusts</td>
<td>b</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Thunderstorm winds</td>
<td>c</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Hurricane and/or tornado event frequency and intensity</td>
<td>c</td>
<td>3</td>
</tr>
<tr>
<td>Sea level elevation</td>
<td></td>
<td>a</td>
<td>2</td>
</tr>
<tr>
<td>Fog</td>
<td></td>
<td>c</td>
<td>3</td>
</tr>
<tr>
<td>Ice</td>
<td>River or lake ice build-up</td>
<td>c</td>
<td>3</td>
</tr>
<tr>
<td>Hail</td>
<td>Frequency of events</td>
<td>c</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Magnitude of events</td>
<td>c</td>
<td>3</td>
</tr>
<tr>
<td>Frost</td>
<td>Freeze-thaw cycles</td>
<td>a</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Frost season length</td>
<td>a</td>
<td>1</td>
</tr>
<tr>
<td>Ice accretion</td>
<td>Frequency and intensity of ice storm events</td>
<td>c</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Ice build up on infrastructure elements</td>
<td>c</td>
<td>3</td>
</tr>
</tbody>
</table>

¹ Note that the availability of observed climate data is very site-specific and depends largely on the density of weather stations for a given area.

Data availability is listed in three categories:
a = generally widely available throughout Canada; data can be extrapolated over a large area
b = relevant where weather station density is sufficiently high
c = available but site specific (results cannot be extrapolated over a large area; weather stations may miss events)

² Three levels of confidence in results are listed:
1 = highly confident
2 = fairly confident
3 = requires further analysis

³ More in-depth analysis required to establish scenarios for future Intensity Duration Frequency (IDF) curves

⁴ Requires clear definition
While climate models can generate results for practically any climate element, they remain most reliable for temperature and precipitation indices. Indeed, both the data from the models and the processes to obtain them must be validated by the scientific community. As research continues in this field and additional validation work is done, more products become available, although this depends largely on the needs expressed by end-users and the importance that is given to produce this type of information. One of the main problems linked to data availability stems from a lack of observed data, namely for events that are very localized in time and space which, by nature, are rare. As well, the timeframe in which the Public Infrastructure Engineering Vulnerability Committee case studies needed to be produced made it difficult to provide a wide array of analyses and scenarios of climate change on a variety of validated climate elements judged important for the vulnerability assessments. It was therefore necessary to generate estimates based on a combination of methods that, for the most part, involved a trend analysis of recent historical data, or estimates based on judgement and consultation with local officials, scientists and climatologists at OURANOS and Environment Canada.

If a relevant climatic factor could not be estimated with any confidence it was classified as unknown and considered a vulnerability.

Because of the inherent variability of the climate and the fact that significant changes can be observed from year to year (a very cold winter followed by a very mild winter the following year for example), there are some nuances to take into account when working with climate scenarios. The following graph illustrates, using temperature indices, how, despite changes in the 30-year averages, the climate will continue to be variable.

Illustrated is the time series of mean surface air temperature for the Canadian land area from the Canadian Global Climate Model 2nd Edition (CGCM2) simulation forced by the Special Report on Emissions Scenarios (SRES) A2 emissions scenario. The blue line indicates the 30-year mean or the 1961-1990 baseline period, whilst the red lines indicate the 30-year mean values for the 2020s (2010-2039), the 2050s (2040-2069) and the 2080s (2070-2099). Scenarios are constructed by calculating the difference, or ratio, between the time means of the future and baseline periods, depending on the climate variable under consideration.

While this process focused on the direct impacts of climate changes to the infrastructure, it may have neglected the indirect impacts of changes to the biophysical environment and those impacts on infrastructure. For example, changes in climate can affect the frequency and location of landslides, increased forest fires can significantly change the flooding regime of a watershed, etc.

Climate scenarios for some of the case studies (see Appendix B) kept many figures after the decimal, introducing a notion that the level of precision is quite high. However, it is important to keep in mind that uncertainties remain and the relevant number should not exceed, in most cases, one figure after the decimal.
6 Water Resources Infrastructure

Water is vital to many sectors and aspects of life in Canada – including agriculture, industries, local governments, energy production, recreation and aquatic systems.

Research and scientific literature present mounting evidence that climate changes will alter where, when and how precipitation falls and water flows. This, in turn, will impact the quantity and quality of surface water and groundwater.

Water’s essential importance to human health, the economy and the environment, means water resource facilities are among the most critical and perhaps the most vulnerable categories of infrastructure relative to climate change. Many questions remain regarding climate change’s impact on water resources infrastructure and how water resources infrastructure can and will respond to climate change. This report forms part of the search for answers.

6.1 Background

Aspects of water resources likely to be influenced by climate changes include the following.

- Seasonal shifts in stream flows in glacier and snowmelt-fed rivers that could lead to increased winter flows and decreases in other seasons. This could impact water storage and electrical power generation and cause possible flooding. In the longer term, this also means depletion of water storage.
- Greater and more intense precipitation events and lengthened dry spells in given locations could increase both flooding and drought.
- Higher water temperature and more intense precipitation, accompanied by extended periods of lower flows, could increase water pollution. By extension, this could impact the ecosystems, human health as well as the reliability and operating costs of water systems.
- Droughts and decreased availability of water may reduce streamflows, lower lake and reservoir levels, depleted soil-moisture reserves and diminished groundwater reserves. By extension, this will likely aggravate water conflicts between various users.
- Sea level rises could extend existing areas of salinization of groundwater estuaries leading to less available freshwater for human populations and ecosystems.

Generally, higher evaporation associated with warming trends tends to offset effects of more precipitation while magnifying the effect of less precipitation.

Climatic shifts and resulting changes in available water resources could require modifications in the water allocations. Such changes could require adjustments to the design, construction, maintenance and operation of water resource infrastructures supplying municipal, industrial and agricultural water users. It could prompt consideration of the robustness, vulnerability, adaptive capacity of current infrastructure, as well as whether additional water resource infrastructure might be needed.

Some specific categories of water resource infrastructure that might be subject to climate-change consideration are listed below.
DAMS, RESERVOIRS AND HYDROPOWER
Dams help to reduce flooding, allow harnessing of energy and provide for reliable water sources for domestic, industrial and agricultural use. In 2002, Canada had 849 large dams, most of them associated with (70%) hydroelectric generation, a field in which Canada leads the world in installed capacity. Issues arising in connection with dams include long-term supply and availability of water. Changes in precipitation patterns raise questions about erosion, dam failure, safety and contingency planning. As noted, besides supporting electrical generation, dams along with diversions and dykes, can control or reduce flooding.

WATER DIVERSION
Pressures could mount for increased water diversion by means of conveyance and storage infrastructure – possibly to allow water transfers over long distances.

IRRIGATION AND DRAINAGE INFRASTRUCTURE
About 85% of agricultural water withdrawals in Canada are used for irrigation with the rest utilized for watering livestock. The Prairies, and particularly Alberta, account for the bulk of irrigated lands in Canada. Much of the irrigation water used is spring snowmelt captured behind dams or reservoirs. Climate change could increase needs for dams, reservoirs and diversions to meet added demand for irrigation. Other adaptive infrastructure traditionally used – such as wells, pipelines and dugouts – may also be called into use.

Besides obtaining water when there is too little, agriculture must remove excess water from crop-producing areas – often via drainage ditches. Climate change may produce increased run-off and require added infrastructure to handle this water.

MUNICIPAL WATER SUPPLY AND TREATMENT
Climate change could affect municipal water systems and supply sources. The timing and availability of water could vary if annual and season rainfall increase, and if rainfall events are more frequent and intense. Higher temperatures could reduce available water or cause droughts leading to water supply shortages. Changing patterns of flooding, and ice jams and build-up could affect intakes of water systems. Both drought and flooding could require additional treatment of the water, thereby placing further demands on treatment plants. (See the City of Portage la Prairie – Water Resources Infrastructure Assessment case study, which is presented in Appendix B.1, for a more detailed analysis of how climate change could impact municipal water supply and treatment infrastructure.)

INDUSTRIAL WATER SUPPLY
Water is critical to manufacturing and thermal power production for cooling, condensing and steam generation, and for conveying waste material. Higher temperatures may increase industrial demand by industry for cooling at a time when water supplies could become scarcer.

NAVIGATION
Inland navigation through the St. Lawrence Waterway, the Great Lakes and related canal systems are likely to be affected by fluctuating water levels. This creates uncertainty for navigation and may add to transportation costs through the need for dredging and vessel redesign. Extreme weather events, including ice storms and storm surges, could create safety concerns for shipping.
Coastal Water Issues
For Canada, with a total coastline exceeding 203,000 kilometres, forecast rises in the mean sea level due to climate change is a significant water resource issue. Two regions of particular concern are Atlantic Canada – including the coasts of Nova Scotia, Prince Edward Island and New Brunswick – plus the Beaufort Sea coast. Specific areas of concern exist in Quebec, British Columbia, and in Newfoundland and Labrador. (For a more detailed assessment of climate change impacts on coastal areas, see the case study on the Town of Placentia, Newfoundland, water resources infrastructure, presented in Appendix B.2.) New or modified infrastructure, or adjusted practices may be required to respond to altered wave patterns, storm surges, and to changes in the duration and thickness of seasonal ice cover.

(For more detailed information on water resources infrastructure impacts, please see Engineering Literature Review: Water Resources – Infrastructure Impacts, Vulnerabilities and Design Considerations for Future Climate Change included as Appendix C.1 of this report.)

6.2 Water Resources Infrastructure Case Study Results
Two water resources infrastructure case studies conducted as part of this engineering vulnerability assessment focused on:

- the City of Portage la Prairie – Manitoba; and
- the Town of Placentia – Newfoundland and Labrador.

High-level summaries of the case studies can be found in Appendix A. Comprehensive reports for each case study are presented in Appendix B.

Engineering vulnerability assessment employs a three dimensional analysis of:

- infrastructure components;
- the way those components respond to climate events; and
- the particular set of climate events under consideration.

Within the Protocol, these factors are used to establish a matrix that guides the analysis. As such, they are considered to be the related through that matrix and the engineering vulnerability analysis. These relationships, or dependencies, are the basis for the engineering vulnerability assessment. The factors chosen for the engineering vulnerability assessment depend on the infrastructure itself, its history, location and the set of climate events that are deemed relevant based on the judgement of the engineering assessment team. Although, the selection of these parameters is the purview of the engineering assessment team, often teams can gain insight from the factors considered in other, similar, assessments. To aid in this process, this report outlines the factors that were included in each of the seven infrastructure case studies. Since the factors are tightly related through the three dimensional engineering vulnerability assessment, they are presented in one table.

Table 2 outlines the factors that were selected for water resources engineering vulnerability assessments based on the results from the Portage la Prairie water works and Placentia water resources case studies.
Table 2: Factors Used in Water Resources Engineering Vulnerability Assessments (Based on two case studies)

<table>
<thead>
<tr>
<th>Relevant Infrastructure Elements</th>
<th>Performance Response</th>
<th>Relevant Climate Events and other Environmental Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Administration &amp; Operations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Personnel</td>
<td>Structural Integrity</td>
<td>Floods - Ice Jamming - Ice Build-up</td>
</tr>
<tr>
<td>• Facilities, Equipment</td>
<td>Serviceability</td>
<td></td>
</tr>
<tr>
<td>• Records*</td>
<td>Functionality</td>
<td>High Temperature</td>
</tr>
<tr>
<td>Dams</td>
<td>Operations &amp; Maintenance</td>
<td>Low Temperature</td>
</tr>
<tr>
<td>• Reservoir</td>
<td>Emergency Response Risk</td>
<td>Intense Rain</td>
</tr>
<tr>
<td>• River System</td>
<td>Insurance Considerations</td>
<td>Drought</td>
</tr>
<tr>
<td>• Diversion Systems*</td>
<td>Policies &amp; Procedures</td>
<td>Ice Storm</td>
</tr>
<tr>
<td>• Dam Structure</td>
<td>Economics</td>
<td>Blizzard</td>
</tr>
<tr>
<td>• Intake Well Pumps</td>
<td>Public Health &amp; Safety</td>
<td>Intense Wind – Tornado</td>
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<tr>
<td>• Flood Wall*</td>
<td>Environmental Effects</td>
<td>Hail</td>
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<tr>
<td>• Breakwater</td>
<td>Stability</td>
<td>Frost Penetration</td>
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<tr>
<td>Treatment</td>
<td>Life Cycle</td>
<td>Groundwater Table</td>
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<tr>
<td>• Pre-treatment</td>
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<td>• Softening, Clarification</td>
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<td>• Filtration*</td>
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<td>• Disinfection</td>
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<td>• Storage</td>
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<tr>
<td>• Chemical Feed Systems*</td>
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<td>• Chemical Storage</td>
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<td>• Valves &amp; Pipes</td>
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<td>Distribution</td>
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<td>• Pump Stations</td>
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<td>• Pipelines &amp; Valves</td>
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<td>• Pipe Materials</td>
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<td>Electric Power</td>
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<td>• Substations</td>
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<td>• Transmission</td>
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<td>• Standby Generators</td>
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<td>Transportation</td>
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<td>• Maintenance Facilities</td>
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<td>Communications</td>
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<td></td>
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<tr>
<td>• Telephone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Two-Way Radio*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Telemetry</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Infrastructure components, climate events and environmental factors that were considered and deemed not to contribute significantly to the infrastructure's engineering vulnerability to climate change in the case studies that were conducted. These items were not included in the summary table below but should be considered in future case studies in this infrastructure category.
Table 3 summarizes the vulnerabilities identified by the Portage la Prairie and Placentia case studies.

### Table 3: Water Resource Infrastructure Vulnerabilities Identified by Case Studies (Based on 2 Case Studies)

<table>
<thead>
<tr>
<th>Infrastructure Components</th>
<th>Climate and other Environmental Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Personnel</td>
<td>Flooding, High Temperature, Intense Rain, Drought, Ice Storm, Blizzard, Intense Wind, Flood, Ground Water, Sea Level, Storm Surge, Sea Level + Storm Surge</td>
</tr>
<tr>
<td>Facilities Equipment</td>
<td>Flooding, High Temperature, Intense Rain, Drought, Ice Storm, Blizzard, Intense Wind, Flood, Ground Water, Sea Level, Storm Surge, Sea Level + Storm Surge</td>
</tr>
<tr>
<td>Dams</td>
<td>Flooding, High Temperature, Intense Rain, Drought, Ice Storm, Blizzard, Intense Wind, Flood, Ground Water, Sea Level, Storm Surge, Sea Level + Storm Surge</td>
</tr>
<tr>
<td>Reservoir</td>
<td>Flooding, High Temperature, Intense Rain, Drought, Ice Storm, Blizzard, Intense Wind, Flood, Ground Water, Sea Level, Storm Surge, Sea Level + Storm Surge</td>
</tr>
<tr>
<td>River System</td>
<td>Flooding, High Temperature, Intense Rain, Drought, Ice Storm, Blizzard, Intense Wind, Flood, Ground Water, Sea Level, Storm Surge, Sea Level + Storm Surge</td>
</tr>
<tr>
<td>Dam Structure</td>
<td>Flooding, High Temperature, Intense Rain, Drought, Ice Storm, Blizzard, Intense Wind, Flood, Ground Water, Sea Level, Storm Surge, Sea Level + Storm Surge</td>
</tr>
<tr>
<td>Intake Well Pumps</td>
<td>Flooding, High Temperature, Intense Rain, Drought, Ice Storm, Blizzard, Intense Wind, Flood, Ground Water, Sea Level, Storm Surge, Sea Level + Storm Surge</td>
</tr>
<tr>
<td>Breakwater</td>
<td>Flooding, High Temperature, Intense Rain, Drought, Ice Storm, Blizzard, Intense Wind, Flood, Ground Water, Sea Level, Storm Surge, Sea Level + Storm Surge</td>
</tr>
<tr>
<td>Water Treatment</td>
<td>Flooding, High Temperature, Intense Rain, Drought, Ice Storm, Blizzard, Intense Wind, Flood, Ground Water, Sea Level, Storm Surge, Sea Level + Storm Surge</td>
</tr>
<tr>
<td>Pre-treatment</td>
<td>Flooding, High Temperature, Intense Rain, Drought, Ice Storm, Blizzard, Intense Wind, Flood, Ground Water, Sea Level, Storm Surge, Sea Level + Storm Surge</td>
</tr>
<tr>
<td>Softening Clarification</td>
<td>Flooding, High Temperature, Intense Rain, Drought, Ice Storm, Blizzard, Intense Wind, Flood, Ground Water, Sea Level, Storm Surge, Sea Level + Storm Surge</td>
</tr>
<tr>
<td>Disinfection</td>
<td>Flooding, High Temperature, Intense Rain, Drought, Ice Storm, Blizzard, Intense Wind, Flood, Ground Water, Sea Level, Storm Surge, Sea Level + Storm Surge</td>
</tr>
<tr>
<td>Storage</td>
<td>Flooding, High Temperature, Intense Rain, Drought, Ice Storm, Blizzard, Intense Wind, Flood, Ground Water, Sea Level, Storm Surge, Sea Level + Storm Surge</td>
</tr>
<tr>
<td>Chemical Storage</td>
<td>Flooding, High Temperature, Intense Rain, Drought, Ice Storm, Blizzard, Intense Wind, Flood, Ground Water, Sea Level, Storm Surge, Sea Level + Storm Surge</td>
</tr>
<tr>
<td>Valves &amp; Pipes</td>
<td>Flooding, High Temperature, Intense Rain, Drought, Ice Storm, Blizzard, Intense Wind, Flood, Ground Water, Sea Level, Storm Surge, Sea Level + Storm Surge</td>
</tr>
</tbody>
</table>
In the above table, high vulnerability elements are depicted in red while moderate vulnerability elements are depicted in yellow. These scales of vulnerability are defined as follows.

High Vulnerability – Based on professional judgement (engineering and operational), there is a high risk of reduced or limited performance and perhaps even failure of the element due to the indicated climatic factor. High vulnerabilities will require remedial action in the short-to-medium term. In many cases, the design can accommodate these changes in the operating environment. However, in other cases, vulnerabilities can occur that require review, prioritization and, for this level of...
vulnerability, are severe enough to require mitigation and/or adaptive strategies to compensate for the vulnerability. These actions may range from retrofitting or rehabilitating the component to changes in operations/maintenance procedures or to more detailed engineering analysis.

A high vulnerability may also exist if there is insufficient information or too many unknowns to make a professional judgement. The reader should refer to the individual case studies for more specific recommendations that are applicable to that particular infrastructure.

Moderate Vulnerability – Based on professional judgement, there is a moderate risk of failure of the component from an interaction with the identified climatic factor. Moderate vulnerabilities will require remedial action in the medium-to-longer term and would involve specific actions that are likely lower in scope and cost compared to higher vulnerabilities.

The number of instances where the vulnerability has been identified through the case studies is identified numerically in the table.

The case study results presented in Table 2, allows the following observations to be made:

- Dam structures and seawalls in these locations may become more vulnerable to flooding.
- Intake structures, on the Prairies in particular, may be vulnerable to drought conditions restricting feed water supply to potable water treatment facilities.
- Intense winds, particularly tornado conditions, present a risk to variety of infrastructures. In this case the probability of the event was generally determined to be very small. However, the consequence of the event was extreme.
- Ice storm events were determined to create a vulnerability to power supply systems putting the water resources infrastructure at risk. In Portage la Prairie, the consultants recommend enhanced standby power-generation facilities.
- In Placentia, the most important risk factor was determined to be a combination of rising sea level and storm surge. At the Public Infrastructure Engineering Vulnerability Committee Workshop, participants agreed that similar risks are being faced by most coastal infrastructure in Canada and recommended that the next series of engineering vulnerability assessments include case studies of coastal infrastructure.

6.2.1 Observations and Conclusions
Based on the work conducted in these assessments and the advice of experts working with the Vulnerability Committee, the following observations and conclusions were reached regarding water resources infrastructure in Canada.

- Water resources systems generally are vulnerable to electrical power interruption. The presence of standby power is particularly important in mitigating vulnerabilities to intense and disruptive weather events.
- For water resources infrastructure, sea level rise and storm surges are common concerns for both the east and west coasts of Canada.
- As with other infrastructure, effective asset management processes can mitigate the vulnerability to climate change of water resource infrastructure.
• The additive effects of multiple climate change factors are important (for example, a combination of low flow and drought). The cumulative effects of several factors, when combined, generally can have significantly more impact than one factor alone.
• Good documentation – historical, current, and in the future – should remain an ongoing priority in dealing with vulnerability.

Based on these case studies and the input from experts at the Public Infrastructure Engineering Vulnerability Committee Workshop, the following recommendations were made regarding Water Resources Infrastructure:

• Ensure access to appropriate standby power.
• Develop guidelines for acceptable level of risk and adapt them to meet local circumstances.
• Make good documentation maintenance a priority.
• Assess First Nations community infrastructure – including water resources – for climate change impacts.

7 Stormwater and Wastewater

Canada has huge investments in stormwater and wastewater infrastructure. In fact, apart from roadways and bridges, Canada's sanitary sewers and sewage treatment facilities collectively represent the infrastructure category with the greatest total capital investment. The pervasiveness of stormwater and wastewater infrastructure in Canada, and the fact that climate events affecting these infrastructures are already being felt across the country, motivated the Vulnerability Committee to treat stormwater and wastewater infrastructure as a high priority for the first national engineering vulnerability assessment.

7.1 Background

Understandably, the design and magnitude of the country's stormwater and wastewater systems vary greatly depending on location and the features of the communities served. Stormwater and wastewater infrastructure have many components, including:

• collection and transmission structures – gutters, pipes, streets, channels, swales, urban creeks and streams, and pumps;
• quantity-control structures – ponds, urban lakes and infiltration devices and roof tops;
• quality-control structures (e.g., grit chambers);
• storage structures;
• overflow systems for carrying both waste and stormwater;
• water treatment facilities; and
• discharge systems for the release of treated water.

The infrastructure will vary depending on whether it entails:

• a combined system carrying wastewater and stormwater in the same system;
• a fully separated system carrying wastewater and stormwater in separate systems; or
• a partially separated system with some divided wastewater and stormwater flows.
The configuration present can affect the degree to which climate change impacts stormwater and wastewater infrastructure. Such climate changes could increase the rainfall events, their annual volume, frequency and intensity. All of these factors might place added demands on collection and treatment systems.

(More information on related research is found in *Literature Review Stormwater and Wastewater – Infrastructure Impacts, Vulnerabilities and Design Considerations for Future Climate Change*, included as Appendix C.2 of this report.)

Temperature changes are other influencing factors on wastewater and stormwater infrastructure. Warmer weather could decrease base flows and affect odour in discharge processes. During drier periods, dry soil could increase the possibility of pipe failures. Higher water temperatures could intensify pollution and adversely affect ecosystems, human populations and the reliability and cost of the collection and treatment systems.

Changing ice regime, including ice jams, could affect drainage systems. Sudden and intense precipitation events arising from climate change may overtax wastewater and stormwater infrastructure, and possibly cause localized flooding.

More than in the case of many other categories of infrastructure, localized and short-duration weather events can severely impact wastewater and stormwater drainage. Generally, current historical data available are too broad in space and time intervals (usually in daily, monthly or even seasonal time steps). This makes it difficult to provide climate projections useful for gauging how vulnerable parts of a storm and wastewater system are to intense and successive weather events, such as flash floods.

As with other infrastructure, receding permafrost could adversely affect wastewater systems, including the stability of sewage storage lagoons, in parts of northern Canada.

Changing conditions that affect the performance or cause failure of wastewater and stormwater systems represent a threat not only to the infrastructure itself but also to human health and safety, the economy and the environment.

### 7.2 Stormwater and Wastewater Case Study Results

One stormwater and wastewater infrastructure case study was conducted as part of this engineering vulnerability assessment. The infrastructure is located in Metro Vancouver, British Columbia.

A high-level summary of the case study can be found in Appendix A. A comprehensive report for the case study is presented in Appendix B.

Engineering vulnerability assessment employs a three-dimensional analysis of:

- infrastructure components;
- the way those components respond to climate events; and
- the particular set of climate events under consideration.
Within the Protocol, these factors are used to establish a matrix that guides the analysis. As such, they are considered to be the related through that matrix and the engineering vulnerability analysis. These relationships, or dependencies, are the basis for the engineering vulnerability assessment. The factors chosen for the engineering vulnerability assessment depend upon the infrastructure itself, its history, location and the set of climate events that are deemed relevant based on the judgement of the engineering assessment team. Although, the selection of these parameters is the purview of the engineering assessment team, often teams can gain insight from the factors considered in other, similar, assessments. To aid in this process, this report outlines the factors that were included in each of the seven infrastructure case studies. Since the factors are tightly related through the three-dimensional engineering vulnerability assessment they are presented in one table.

Table 4 outlines the factors that were considered in the engineering vulnerability assessment conducted in Metro Vancouver.
Table 4: Factors Considered in the Stormwater and Wastewater Engineering Vulnerability Assessment

<table>
<thead>
<tr>
<th>Relevant Infrastructure Elements</th>
<th>Performance Response</th>
<th>Relevant Climate Events and other Environmental Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Collection Systems</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>* Physical Infrastructure</td>
<td>Structural Integrity</td>
<td>Intense Rain</td>
</tr>
<tr>
<td>o Combined Sewer Trunks</td>
<td>Serviceability</td>
<td>Total</td>
</tr>
<tr>
<td>o Combined Sewer Interceptors</td>
<td>Functionality</td>
<td>Annual/Seasonal Rain</td>
</tr>
<tr>
<td>o Sanitary Mains</td>
<td>Operations &amp;</td>
<td>Sea Level</td>
</tr>
<tr>
<td>o Siphons*</td>
<td>Maintenance</td>
<td>Storm Surge</td>
</tr>
<tr>
<td>o Outfalls*</td>
<td>Emergency Response</td>
<td>Floods</td>
</tr>
<tr>
<td>o Pump Stations &amp; Wet Wells</td>
<td>Risk</td>
<td>Temperature High*</td>
</tr>
<tr>
<td>o Manholes</td>
<td>Insurance Considerations</td>
<td></td>
</tr>
<tr>
<td>o Flow &amp; Level Monitors</td>
<td>Policies &amp; Procedures</td>
<td>Drought*</td>
</tr>
<tr>
<td>o Flow Control Structures</td>
<td>Economics</td>
<td>Extreme Winds</td>
</tr>
<tr>
<td>o Grit Chambers*</td>
<td>Public Health &amp; Safety</td>
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</tr>
<tr>
<td></td>
<td>Environmental Effects</td>
<td></td>
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<tr>
<td><strong>Supporting Systems</strong></td>
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<tr>
<td>o Power</td>
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<tr>
<td>o Communication</td>
<td></td>
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<tr>
<td>o Transportation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>o Personnel, Facilities &amp; Equipment*</td>
<td></td>
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<tr>
<td>o Records</td>
<td></td>
<td></td>
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<tr>
<td><strong>Treatment</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>* Process</td>
<td></td>
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<tr>
<td>o Screening</td>
<td></td>
<td></td>
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<tr>
<td>o Influent Pumping</td>
<td></td>
<td></td>
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<tr>
<td>o Grit Removal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>o Primary Clarification</td>
<td></td>
<td></td>
</tr>
<tr>
<td>o Sludge Thickening*</td>
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<td></td>
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<tr>
<td>o Sludge Digestion</td>
<td></td>
<td></td>
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<tr>
<td>o Sludge Lagoons</td>
<td></td>
<td></td>
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<tr>
<td><strong>Hydraulics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>o Treatment Liquid-Stream</td>
<td></td>
<td></td>
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<tr>
<td>o Effluent Disposal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>**Supporting Systems / Infrastructure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>o On-site Pipelines</td>
<td></td>
<td></td>
</tr>
<tr>
<td>o Buildings, Tankage &amp; Housed Equipment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>o Standby Generators</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Infrastructure components, climate events and environmental factors that were considered and deemed not to contribute significantly to the infrastructure’s engineering vulnerability to climate change in the case studies that were conducted. These items were not included in the summary table below but should be considered in future case studies in this infrastructure category.
Table 5 summarizes the vulnerabilities identified by the Metro Vancouver case study.  

**Table 5: Stormwater and Wastewater Infrastructure Vulnerabilities Identified by Case Study**

<table>
<thead>
<tr>
<th>Infrastructure Components</th>
<th>Climate and other Environmental Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Intense Rain</td>
</tr>
<tr>
<td>Collection Systems</td>
<td></td>
</tr>
<tr>
<td>Physical Infrastructure</td>
<td></td>
</tr>
<tr>
<td>Combined Sewer Trunks</td>
<td>1</td>
</tr>
<tr>
<td>Combined Sewer Interceptors</td>
<td>1</td>
</tr>
<tr>
<td>Sanitary Mains</td>
<td>1</td>
</tr>
<tr>
<td>Pump Stations &amp; Wet Wells</td>
<td>1</td>
</tr>
<tr>
<td>Manholes</td>
<td>1</td>
</tr>
<tr>
<td>Flow &amp; Level Monitors</td>
<td>1</td>
</tr>
<tr>
<td>Flow Control Structures</td>
<td>1</td>
</tr>
<tr>
<td>Supporting Systems</td>
<td></td>
</tr>
<tr>
<td>Power</td>
<td></td>
</tr>
<tr>
<td>Communication</td>
<td></td>
</tr>
<tr>
<td>Transportation</td>
<td></td>
</tr>
<tr>
<td>Records</td>
<td>1</td>
</tr>
<tr>
<td>Treatment/ Process</td>
<td>Climate and other Environmental Factors</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>-----------------------------------------</td>
</tr>
<tr>
<td></td>
<td>Intense Rain</td>
</tr>
<tr>
<td>Screening</td>
<td></td>
</tr>
<tr>
<td>Influent Pumping</td>
<td></td>
</tr>
<tr>
<td>Grit Removal</td>
<td></td>
</tr>
<tr>
<td>Primary Clarification</td>
<td></td>
</tr>
<tr>
<td>Sludge Digestion</td>
<td></td>
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<tr>
<td>Sludge Lagoons</td>
<td></td>
</tr>
<tr>
<td>Hydraulics</td>
<td></td>
</tr>
<tr>
<td>Treatment Liquid-Stream</td>
<td></td>
</tr>
<tr>
<td>Effluent Disposal</td>
<td></td>
</tr>
<tr>
<td>Supporting Systems / Infrastructure</td>
<td></td>
</tr>
<tr>
<td>On-site Pipelines</td>
<td></td>
</tr>
<tr>
<td>Buildings, Tankage &amp; Housed Equipment</td>
<td></td>
</tr>
<tr>
<td>Standby Generators</td>
<td></td>
</tr>
</tbody>
</table>

Key:
- [ ] High Vulnerability
- [ ] Medium Vulnerability
- # Number of Cases Observed
In the above table, high vulnerability areas are depicted in red while moderate vulnerability areas are depicted in yellow. The number of instances where the vulnerability has been identified through the case study is identified numerically in the table.

**High Vulnerability** – Based on professional judgement (engineering and operational), there is a high risk of reduced or limited performance and perhaps even failure of the element due to the indicated climatic factor. High vulnerabilities will require remedial action in the short-to-medium term. In many cases, the design can accommodate these changes in the operating environment. However, in other cases, vulnerabilities can occur that require review, prioritization and, for this level of vulnerability, are severe enough to require mitigation and/or adaptive strategies to compensate for the vulnerability. These actions may range from retrofitting or rehabilitating the component to changes in operations/maintenance procedures or to more detailed engineering analysis.

A high vulnerability may also exist if there is insufficient information or too many unknowns to make a professional judgement. The reader should refer to the individual case studies for more specific recommendations that are applicable to that particular infrastructure.

**Moderate Vulnerability** – Based on professional judgement there is a moderate risk of failure of the component from an interaction with the identified climatic factor. Moderate vulnerabilities will require remedial action in the medium-to-longer term and would involve specific actions that are likely lower in scope and cost compared to higher vulnerabilities.

The number of instances where the vulnerability has been identified through the case studies is identified numerically in the table.

Based on the case study results presented in Table 4, the following observations can be made.

- In Metro Vancouver, sewer trunks, interceptors and sanitary mains are vulnerable to an increase in intense rain events.
- Common with the Placentia case study, coastal infrastructure is vulnerable to storm surge.
- Generally, the stormwater and wastewater infrastructure in Metro Vancouver is resilient.

### 7.2.1 Observations and Conclusions

Based on the work conducted in these assessments and the advice of experts working with the Vulnerability Committee, the following observations and conclusions were reached regarding stormwater and wastewater infrastructure in Canada:

- Stormwater and wastewater systems are vulnerable, generally, to electrical-power interruption. The presence of standby power is particularly important in mitigating vulnerabilities to intense and disruptive weather events.
- Traditionally, flood-plain mapping is historical in nature and draws upon past experience. Such mapping should be projective into the future and reflect relevant climate change factors. This approach will require the use of regional climate models and ongoing consultation between engineers, planners and climate scientists to ensure that there is a common understanding of the data needs and data quality.
• For stormwater and wastewater infrastructure, sea-level rise and storm surges are common concerns for both the east and west coasts of Canada.
• As with other infrastructure, effective asset management processes can mitigate the vulnerability to climate change of stormwater and wastewater infrastructure.
• The additive effects of multiple climate change factors are important. (For example, a combination of low flow and drought). The cumulative effects of several factors, when combined, generally can have significantly more impact than one factor alone.
• Good documentation – historical, current, and in the future – should remain an ongoing priority in dealing with vulnerability.

Based on these case studies and the input from experts at the Public Infrastructure Engineering Vulnerability Committee Workshop, the following recommendations are made regarding stormwater and wastewater infrastructure:

• Ensure access to appropriate standby power.
• Make the decline in Ontario lake levels (especially the Great Lakes) a focus of future vulnerability assessments.
• Develop guidelines for acceptable level of risk and adapt them to meet local circumstances.
• Conduct future-oriented (rather than historically-based) flood-plain mapping.
• Make good documentation maintenance a priority.
• Develop representative case studies of stormwater and wastewater infrastructure in northern communities.
• Assess First Nations community infrastructure – including water resources, stormwater and wastewater systems – for climate change impacts.

8 Roads and Associated Structures

Canada’s roadway infrastructure spans a great variety of terrain. The country’s approximately one million kilometres of highways, roads and streets; about 56,000 bridges and other associated infrastructure come in many shapes and sizes, and with differing surfaces and foundations. Relative to other public infrastructure, the dollar value of Canada’s roadway and bridge capital stock dwarfs that of other categories of infrastructure.

Like other infrastructure, roads and bridges are not expected to escape the effects of climate change. While road agencies are giving thought to how climate change will affect roads systems, again, as with some other categories of infrastructure, little documented information is so far available examining the topic. The roads and associated structure infrastructure case studies documented in the appendices in this report move toward filling this gap.

Traditionally, roadway design in Canada has proceeded on the assumption of static climate conditions where historic weather data provided adequate roadmaps for future designs.
8.1 Background

Trends toward higher temperature and changing precipitation patterns will sometimes yield possible benefits and in other instances will exact a toll on roads. Innovative approaches to road, pavement and bridge design, and management may emerge to meet these new challenges.

**Roads**

Experts specifically expect climate change to influence phenomena relating to thermal cracking; frost heave; thaw weakening; and permafrost melting and deformation.

Higher average winter temperatures can be expected to bring on shorter freezing seasons where roadways are subject to later freezing and earlier thawing.

Higher in-service temperature for roadways could increase the potential for rutting and generally, maintenance, rehabilitation and reconstruction will be needed earlier in the design life.

Warmer winters may reduce the amount of snow clearing necessary and may lead to adoption of different sand and salt mixes. Snow roads, often used to access northern locations in winter, can be expected to have shorter operating windows. Shortened freeze-ups also could change the duration of seasonal road restrictions. Receding permafrost could affect roadways originally built on ground that was frozen year-round.

Roadways, particularly low-lying ones, could become more vulnerable to flooding from added precipitation, more frequent and more intense rainstorms, or from overflowing steams and water bodies.

Added precipitation would increase soil moisture, rendering slopes unstable and more likely to produce landslides that could damage or close roads and bridges.

**Bridges**

Longer and more frequent weather events could make some bridges and culverts vulnerable and cause loss of the infrastructure. Bridges may need modification of design, construction and maintenance to account for additional flooding. This is especially true for low-lying bridges.

(For more detailed information on water resources infrastructure impacts, please see Engineering Literature Review: Roads and Associated Structures: Infrastructure Impacts, Vulnerabilities and Design Considerations for Future Climate Change included as Appendix C.3 of this report.)

8.2 Roads and Associated Structures Case Study Results

Two roads and associated structure infrastructure case studies were conducted as part of this engineering vulnerability assessment. The case studies focused on:

- the City of Greater Sudbury – Ontario; and
- the City of Edmonton Quesnell Bridge Refurbishment – Alberta.
Engineering vulnerability assessment employs a three-dimensional analysis of:

- infrastructure components;
- the way those components respond to climate events; and
- the particular set of climate events under consideration.

Within the Protocol, these factors are used to establish a matrix that guides the analysis. As such, they are considered to be the related through that matrix and the engineering vulnerability analysis. These relationships, or dependencies, are the basis for the engineering vulnerability assessment. The factors chosen for the engineering vulnerability assessment depend on the infrastructure itself, its history, location and the set of climate events that are deemed relevant based on the judgement of the engineering assessment team. Although, the selection of these parameters is the purview of the engineering assessment team, often teams can gain insight from the factors considered in other, similar, assessments. To aid in this process, this report outlines the factors that were included in each of the seven infrastructure case studies. Since the factors are tightly related through the three-dimensional engineering vulnerability assessment they are presented in one table.

High-level summaries of the case studies can be found in Appendix A. Comprehensive reports for each case study are presented in Appendix B.

Table 6 outlines the factors that were considered in the engineering vulnerability assessments conducted in Sudbury and Edmonton. Since the case studies evaluated different sets of infrastructure components, those components unique to roads and bridges have been outlined separately in this table. However, the performance response and climate events are relevant and useful guidance for all categories of roads and bridges vulnerability assessment, and have not been split out in the table.
Table 6: Factors Considered in Roads and Associated Structures Engineering Vulnerability Assessments

<table>
<thead>
<tr>
<th>Relevant Infrastructure Elements</th>
<th>Performance Response</th>
<th>Relevant Climate Events and other Environmental Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arterial Roads</td>
<td>Structural Integrity</td>
<td>High Temperature</td>
</tr>
<tr>
<td>Collector Roads</td>
<td>Serviceability</td>
<td>Low Temperature</td>
</tr>
<tr>
<td>Local Urban Roads</td>
<td>Functionality</td>
<td>Extreme Temperature Range*</td>
</tr>
<tr>
<td>Local Rural Roads</td>
<td>Operations &amp;</td>
<td>Precipitation as Rain</td>
</tr>
<tr>
<td></td>
<td>Maintenance</td>
<td></td>
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<tr>
<td></td>
<td>Emergency Response</td>
<td>Precipitation as Snow</td>
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<tr>
<td></td>
<td>Risk</td>
<td>Wind</td>
</tr>
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<td></td>
<td>Insurance Considerations</td>
<td>Ice Accretion</td>
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<tr>
<td></td>
<td>Policies &amp; Procedures</td>
<td>ice Force*</td>
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<tr>
<td></td>
<td>Economics</td>
<td>Hail</td>
</tr>
<tr>
<td></td>
<td>Public Health &amp; Safety</td>
<td>Freeze-Thaw Cycles</td>
</tr>
<tr>
<td></td>
<td>Environmental Effects</td>
<td>Ground Water</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Flooding</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fog*</td>
</tr>
<tr>
<td>Bridges</td>
<td></td>
<td>Temperature + Relative Humidity</td>
</tr>
<tr>
<td>Operations &amp; Maintenance</td>
<td></td>
<td>Heavy Winter Snow + Early Spring + Heavy Rain = Major</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Flooding</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Snow/Ice + Freeze Temp = Heavy/Dense Snow</td>
</tr>
</tbody>
</table>

- Surface
- Surface Treatment
- Surface Gravel
- Curb
- Sidewalk
- Traffic Signals
- Street Lighting
- Utility Poles
- Boulevards and Shoulders
- Bike Paths
- Embankments/Cuts
- Bridge/Structures
- Signage
- Sub-Base
- Storm Sewer Systems
- Catch Basins
- Culverts
- Ditches
- Distribution Systems
- Maintenance Holes
- Underground Utilities
- Administration/Personnel
- Maintenance
- Winter Maintenance
- Records
- Trees
- Guide Rails

- Regular Maintenance Crew*
- Maintenance Equipment*
- Snow Removal Personnel*
- Snow Removal Equipment / Material*
- Cast-in-place Concrete*
- Reinforcement*
- Wearing Surface
- Water-proofing Membrane
- De-icing System/Approach*
*Infrastructure components, climate events and environmental factors that were considered and deemed not to contribute significantly to the infrastructure's engineering vulnerability to climate change in the case studies that were conducted. These items were not included in the summary table below but should be considered in future case studies in this infrastructure category.
Table 7 summarizes the vulnerabilities identified by the Sudbury and Edmonton case studies.

The Sudbury case study evaluated four different components of road infrastructure:

- arterial;
- collector;
- local – urban; and
- local – rural.

For the purposes of Table 6, the results from these assessments were consolidated into a single matrix. Each road type was treated as a separate case study contributing to the overall assessment. The results from the Edmonton study were then consolidated into the same table for analysis.
Table 7: Roads and Associated Structure Vulnerabilities Identified by Case Studies

<table>
<thead>
<tr>
<th>Infrastructure Components</th>
<th>Climate and other Environmental Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High Temp</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Roads</td>
<td></td>
</tr>
<tr>
<td>Surface</td>
<td>3</td>
</tr>
<tr>
<td>Surface Treatment</td>
<td>1</td>
</tr>
<tr>
<td>Surface Gravel</td>
<td>1</td>
</tr>
<tr>
<td>Curb</td>
<td>1</td>
</tr>
<tr>
<td>Sidewalk</td>
<td>2</td>
</tr>
<tr>
<td>Traffic Signals</td>
<td>1</td>
</tr>
<tr>
<td>Street Lighting</td>
<td>3</td>
</tr>
<tr>
<td>Utility Poles</td>
<td>3</td>
</tr>
<tr>
<td>Boulevards and Shoulders</td>
<td>3</td>
</tr>
<tr>
<td>Bike Paths</td>
<td>1</td>
</tr>
<tr>
<td>Embankments/Cuts</td>
<td>1</td>
</tr>
<tr>
<td>Bridge/Structures</td>
<td>1</td>
</tr>
<tr>
<td>Signage</td>
<td>1</td>
</tr>
<tr>
<td>Sub-Base</td>
<td>1</td>
</tr>
<tr>
<td>Storm Sewer Systems</td>
<td>3</td>
</tr>
<tr>
<td>Catch Basins</td>
<td>3</td>
</tr>
<tr>
<td>Culverts</td>
<td>1</td>
</tr>
</tbody>
</table>
In the above table, high vulnerability areas are depicted in red while moderate vulnerability areas are depicted in yellow. The number of instances where the vulnerability has been identified through the case studies is identified numerically in the table.
**High Vulnerability** – Based on professional judgement (engineering and operational) there is a high risk of reduced or limited performance and perhaps even failure of the element due to the indicated climatic factor. High vulnerabilities will require remedial action in the short-to-medium term. In many cases, the design can accommodate these changes in the operating environment. However, in other cases, vulnerabilities can occur that require review, prioritization and, for this level of vulnerability, are severe enough to require mitigation and/or adaptive strategies to compensate for the vulnerability. These actions may range from retrofitting or rehabilitating the component to changes in operations/maintenance procedures or to more detailed engineering analysis.

A high vulnerability may also exist if there is insufficient information or too many unknowns to make a professional judgement. The reader should refer to the individual case studies for more specific recommendations that are applicable to that infrastructure.

**Moderate Vulnerability** – Based on professional judgement there is a moderate risk of failure of the component from an interaction with the identified climatic factor. Moderate vulnerabilities will require remedial action in the medium-to-longer term and would involve specific actions that are likely lower in scope and cost compared to higher vulnerabilities.

The number of instances where the vulnerability has been identified through the case studies is identified numerically in the table.

Based on the case study results presented in Table 6, the following observations are made.

- In general, road systems in Sudbury and on the proposed refurbished Quesnell Bridge were found to be resilient to the climate change scenarios applied in the studies.
- Road surfaces were found to be somewhat vulnerable to increased precipitation events and more frequent freeze-thaw cycles in both Edmonton and Sudbury.
- On the Quesnell Bridge, ice accretion and freeze-thaw cycles were found to create potentially significant vulnerabilities.
- The most significant vulnerability observed for road systems in Sudbury resulted from a projected increase in heavy snow events. This had an impact on snow removal procedures for sidewalks.

**8.2.1 Observations and Conclusions**

Bridges and other infrastructure systems associated with roadway infrastructure were grouped together with roads in this initial assessment. However, based on the results from the Edmonton and Sudbury case studies and input from experts at the Public Infrastructure Engineering Vulnerability Committee Workshop it was concluded that characteristics of road infrastructure differ considerably from those of bridges and certain associated structures. This is particularly notable with respect to design life. While obviously connected to roadway systems, bridges and associated structures, such as culverts and related drainage, typically are projected to last longer than road surfaces.

In terms of climate change, the shorter life cycles of roads mitigate the need for adaptive measures in the near term. Furthermore, failures or catastrophic events involving bridges are likely to have longer-lasting impacts. Usually, roads can be more readily repaired following a disruption.
While Canada's roads pass through an enormous variety of terrain (including rock, soil, muskeg and permafrost), common factors contributing to vulnerability in all regions of the country are inadequate operation, maintenance and asset management.

A number of information shortfalls may impede assessment of the impact of climate changes on road and associated infrastructure. They include:

- the need to consider levels of service and define guidelines on effective levels of service (What is an acceptable level of risk?);
- assessment of what materials have better adaptive capacities;
- required codes revision to reflect more up-to-date climate data relative to concrete, pavement and gravel;
- lack of ice accretion data – a shortfall that can compromise vulnerability assessments;
- need for nationally developed operation and maintenance guidelines to provide consistency and knowledge sharing across country.

Northern roads, especially winter roads, are critical and differ from roads in other regions. As a result, they present particular challenges.

Consequences of drought on subsoil stability and their effect on the vulnerability of roads and bridges need to be addressed in future assessments.

Lifecycle and asset maintenance, and condition analyses/assessments are fundamental to gauging vulnerability. They must be updated regularly. This includes capital and operational costs and often results in more resilient infrastructure.

Future vulnerability assessments should focus on cumulative effects. Consistent with the other case studies, the Edmonton and Sudbury studies found that infrastructure was generally resilient to discrete, one-time, climate events. However, cumulative or cascading events, especially when combined with other infrastructure deficit issues, could result in climate change vulnerability.

Work on roads and associated infrastructure's vulnerability to climate changes resulted in the following recommendations.

- Focus future assessments on roads OR bridges, not roads AND bridges.
- Revise codes to reflect more up-to-date climate data.
- Develop operation and maintenance guidelines nationally to provide consistency and knowledge sharing across the country.
- Make ice roads/temporary roads a focus for future studies.
9 Buildings

Canada's inventory of thousands of buildings exists in a bewildering array of sizes, shapes, designs and configurations, and performs many functions. That is so whether dealing with:

- public infrastructure systems – including government, educational, health, cultural, recreational and other facilities – that are the focus of this report;
- para-public infrastructure – including sports venues and transportation terminals, which though privately owned, receive widespread public use; and
- clearly privately owned structures, including single, detached dwellings.

Somewhat like people, buildings that may appear similar are prone to behave differently, have different quirks and varying “life experiences”. The specifics of location, such as the soil and topography of a building site, plus exposure to wind, precipitation, sun and other environmental elements help determine buildings' traits and durability. Besides features or “personalities” that vary from one building to the next, the characteristics of a specific building may evolve over time through aging, use and, importantly, due to changing weather and climate patterns.

9.1 Background

Traditionally, designers of Canadian buildings relied on the built-in assumption that the climatic patterns present at the time of design and construction would stay fairly constant throughout the structure's useful life. For most buildings in Canada, it has been assumed that they will last at least 50 years.

However, information in this report and from other sources now casts serious doubt on assumptions about climatic conditions staying constant. The data point to possibilities of some fairly rapid climatic changes. Supporting evidence for this comes in the form of increasing temperatures, rising sea levels, higher average wind speeds, as well as changing precipitation patterns. The latter could include changes in the intensity and timing of precipitation, which may affect factors such as snow loads and snow packs.

Shifting climatic phenomena could mean that a building originally designed to meet the demands of, say, a “severe cold zone”, in fact, for much of its lifecycle could be in a “cold zone”. Climate change could leave buildings vulnerable if they are not designed for the prevailing weather conditions they face.

In many cases, climate change could leave Canadian buildings vulnerable to:

- technical inabilities to cope with failures, with resulting harm to occupants, equipment and material;
- disruption or limitations in services delivery; or
- added costs in delivering services.
Engineers, consulting firms and others involved in the design, construction, maintenance, operation and use of buildings will be called upon to identify and respond to such vulnerabilities. Many factors could come into play and have to be considered – among them:

- building materials, building envelopes and building stability;
- accelerated physical weathering, due to changing atmospheric physical, chemical properties and biological – including wind-driven rain and abrasive materials, broad-spectrum solar and ultraviolet radiation; mould, mildew, rot and possible pest infestations;
- effective functioning of air and vapour barriers;
- impacts related to water levels – notably in flood plains, deltas and costal areas;
- changes in ground conditions – including receding permafrost or dry soil conditions;
- shifting daytime and night-time heating patterns;
- wetter conditions (particularly in northern areas) leading to frost penetration, wetting and drying, moisture and penetration of doors, windows and other areas;
- more freeze and thaw cycles – causing water damage from ice-damming on roofs, and break-up of bonded materials and facades;
- maintenance challenges and, due to climate changes, widening of existing infrastructure deficits;
- need to apply revised building codes and standards, as well as design values relating to expected changes in frequency of certain weather events;
- resiliency, strength and durability of materials – including concrete, stone, masonry and plaster – and how they are used;
- structural integrity of walls and roofs in the face of stronger winds, and more frequent and intense precipitation, leading to changing snow patterns and packs; and
- heating ventilation and cooling – including possible lessened reliance on fossil fuels (for heating) and more dependence on electrical power (for cooling).

Changes, considerations and consequences will differ across the country. Furthermore, it is difficult to forecast the magnitude of certain anticipated changes, especially those related to wind, using current climate models.

With rare exceptions, buildings are not stand-alone infrastructure. Almost invariably, buildings need the support of other infrastructure – be it water supply, sewer, roadway, electrical or communications systems. Failures in any of these systems, possibly a sewer backup brought on by sudden flooding, can affect buildings. The buildings, in turn, may house critical components (power generation, water treatment, instrumentation etc.) of the supporting infrastructures. In short, buildings left vulnerable by climate change may expose other infrastructure to vulnerability.

Choices made today for new and existing building could either intensify or mitigate buildings’ vulnerabilities to climate change in coming decades.

(For more detailed information on climate-related impacts on building infrastructure, please see the literature review Public Buildings – Infrastructure Impacts, Vulnerabilities and Design Considerations for Future Climate Change included as Appendix C.4 of this report.)
9.2 Buildings Case Study Results

Two buildings infrastructure case studies were conducted as part of this engineering vulnerability assessment. The case studies focused on:

- thermosyphon foundations – Northwest Territories
- Government of Canada buildings – Ottawa

Engineering vulnerability assessment employs a three-dimensional analysis of:

- infrastructure components;
- the way those components respond to climate events; and
- the particular set of climate events under consideration.

Within the Protocol, these factors are used to establish a matrix that guides the analysis. As such, they are considered to be the related through that matrix and the engineering vulnerability analysis. These relationships, or dependencies, are the basis for the engineering vulnerability assessment. The factors chosen for the engineering vulnerability assessment depend on the infrastructure itself, its history, location and the set of climate events that are deemed relevant based on the judgement of the engineering assessment team. Although, the selection of these parameters is the purview of the engineering assessment team, often teams can gain insight from the factors considered in other, similar, assessments. To aid in this process, this report outlines the factors that were included in each of the seven infrastructure case studies. Since the factors are tightly related through the three-dimensional engineering vulnerability assessment they are presented in one table.

High-level summaries of the case studies can be found in Appendix A. Comprehensive reports for each case study are presented in Appendix B.

Table 8 outlines the factors that were considered in the engineering vulnerability assessments conducted in the Northwest Territories.

**Table 8: Factors Considered in Thermosyphon Engineering Vulnerability Assessments**

<table>
<thead>
<tr>
<th>Relevant Infrastructure Elements</th>
<th>Performance Response</th>
<th>Relevant Climate Events and other Environmental Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thermosyphon Foundations</strong></td>
<td></td>
<td>Air Temperature</td>
</tr>
<tr>
<td>• Evaporator Pipes</td>
<td>Structural Integrity</td>
<td>Ground Temperature</td>
</tr>
<tr>
<td>• Insulation</td>
<td>Serviceability</td>
<td></td>
</tr>
<tr>
<td>• Radiators</td>
<td>Functionality</td>
<td></td>
</tr>
<tr>
<td>• Granular Pads</td>
<td>Operations &amp; Maintenance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Policies &amp; Procedures</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Economics</td>
<td></td>
</tr>
</tbody>
</table>
The Thermosyphon Foundation study in the Northwest Territories was a unique application of the engineering vulnerability assessment methodology. The case study host, the Government of the Northwest Territories, had previously completed preliminary project definition and vulnerability assessment analysis. It concluded that the primary concern was one unique infrastructure element (thermosyphons) and the response of that element to projected increasing air temperatures, which are already being seen in northern Canada. As a result, the thermosyphon study focused on one infrastructure element over ten different sites while the other case studies focused multiple infrastructure elements in one location.

Consistent with other case studies, the case study identified that thermosyphon installations in the Northwest Territories are resilient, at least in the short term, to increasing air temperatures provided that other infrastructure deficit issues are managed. Issues that resonated within the case study included:

- design
- installation;
- ongoing maintenance;
- monitoring the temperature of the thermosyphon foundation over time; and
- monitoring other physical changes at the thermosyphon location that may compromise the performance of the thermosyphon foundation.

The study also identified a potential discontinuity between observed and forecast air temperatures and the impact of this data issue on assessing the vulnerability of northern infrastructure. As part of the study, work was initiated with Environment Canada to address this issue.

The thermosyphon case study presents a model of how to expand the National Engineering Vulnerability Assessment process over the next phase of case studies. In this model, the Protocol is used to identify potential patterns of infrastructure element vulnerability. The vulnerability could then be confirmed by using the thermosyphon methodology to assess the particular infrastructure element regionally and nationally at a number of geographically diverse locations. Based on this process, the next series of case studies could be used to more fully characterize potential climate change vulnerabilities.

Table 9 outlines the factors that were considered in the engineering vulnerability assessments conducted in Ottawa.
Table 9: Factors Considered in Buildings Infrastructure Engineering Vulnerability Assessments

<table>
<thead>
<tr>
<th>Relevant Infrastructure Elements</th>
<th>Performance Response</th>
<th>Relevant Climate Events and other Environmental Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Exterior Systems</strong></td>
<td>Structural Integrity</td>
<td>Air Temperature</td>
</tr>
<tr>
<td>Site Drainage</td>
<td>Serviceability</td>
<td>Rain</td>
</tr>
<tr>
<td>Site Drains</td>
<td>Functionality</td>
<td>Snow and Wind</td>
</tr>
<tr>
<td>Walls</td>
<td>Operations &amp;</td>
<td>Frost Season Length</td>
</tr>
<tr>
<td>• Freestanding</td>
<td>Maintenance</td>
<td>Heating Degree Days</td>
</tr>
<tr>
<td>◦ Concrete</td>
<td>Policies &amp; Procedures</td>
<td>Humidity</td>
</tr>
<tr>
<td>• Retaining</td>
<td>Economics</td>
<td></td>
</tr>
<tr>
<td>◦ Masonry</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Walkways</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Asphalt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Concrete</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Unit Pavers</td>
<td></td>
<td></td>
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<tr>
<td>Stairs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Concrete</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Metal</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Infrastructure components, climate events and environmental factors that were considered and deemed not to contribute significantly to the infrastructure's engineering vulnerability to climate change in the case studies that were conducted. These items were not included in the summary table below but should be considered in future case studies in this infrastructure category.

<table>
<thead>
<tr>
<th>Relevant Infrastructure Elements</th>
<th>Performance Response</th>
<th>Relevant Climate Events and other Environmental Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ramps</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metal Gutters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loading Dock (concrete and enclosed area)*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parking, Vehicle Areas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Asphalt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Concrete</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Unit Pavers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintenance/Access Doors</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Building Systems</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foundations, Floor and Roofs*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Footings – Concrete*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Walls – Concrete*</td>
<td></td>
<td></td>
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<tr>
<td>• Slab on Grade – Concrete*</td>
<td></td>
<td></td>
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<tr>
<td>• Panel Roof*</td>
<td></td>
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<tr>
<td>Envelope Systems</td>
<td></td>
<td></td>
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<tr>
<td>• Precast Concrete</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Glazed Curtain Wall</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Masonry Wall</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Stone Panels (including header and sills)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Metal Cladding</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Windows/Doors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Aluminum Windows</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Doors (Steel/Aluminum)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flat Roof Systems*</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mechanical Systems</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heating System Adequacy</td>
<td></td>
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<tr>
<td>Cooling System Adequacy</td>
<td></td>
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<tr>
<td><strong>Electrical Systems</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emergency Power Systems/ Generators (including fuel supply)*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Supply and Reliability</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Infrastructure components, climate events and environmental factors that were considered and deemed not to contribute significantly to the infrastructure's engineering vulnerability to climate change in the case studies that were conducted. These items were not included in the summary table below but should be considered in future case studies in this infrastructure category.
Table 10 summarizes the vulnerabilities identified by the Ottawa Buildings case study.

**Table 10: Buildings Vulnerabilities Identified by Case Study (Based on One Case Study)**

<table>
<thead>
<tr>
<th>Infrastructure Component</th>
<th>Temperature</th>
<th>Rain</th>
<th>Snow and Wind</th>
<th>Frost Season Length</th>
<th>Heating Degree Days</th>
<th>Humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Drainage</td>
<td></td>
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<td></td>
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<tr>
<td>Site Drains</td>
<td>1</td>
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<td></td>
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</tr>
<tr>
<td>Freestanding Concrete Walls</td>
<td></td>
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<tr>
<td>Freestanding Masonry Walls</td>
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<tr>
<td>Concrete Retaining Walls</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Asphalt Walkways</td>
<td></td>
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<tr>
<td>Concrete Walkways</td>
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<tr>
<td>Unit Paver Walkways</td>
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<tr>
<td>Stairs – Concrete</td>
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<tr>
<td>Stairs – Metal</td>
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<td></td>
</tr>
<tr>
<td>Ramps – Concrete</td>
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<tr>
<td>Metal Gutters</td>
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<tr>
<td>Parking Areas – Asphalt</td>
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<tr>
<td>Parking Areas – Concrete</td>
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<tr>
<td>Parking Areas – Unit Paver</td>
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<td></td>
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<tr>
<td>Manholes/Access Doors</td>
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<tr>
<td>Envelope Systems</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Precast Concrete</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
In the above table, high vulnerability areas are depicted in red while moderate vulnerability areas are depicted in yellow. The number of instances where the vulnerability has been identified through the case study is identified numerically in the table.

**High Vulnerability** – Based on professional judgement (engineering and operational) there is a high risk of reduced or limited performance and perhaps even failure of the element due to the indicated climatic factor. High vulnerabilities will require remedial action in the short-to-medium term. In many cases, the design can accommodate these changes in the operating environment. However, in other cases, vulnerabilities can occur that require review, prioritization and, for this level of vulnerability, are severe enough to require mitigation and/or adaptive strategies to compensate for the vulnerability. These actions may range from retrofitting or rehabilitating the component to changes in operations/maintenance procedures or to more detailed engineering analysis.
A high vulnerability may also exist if there is insufficient information or too many unknowns to make a professional judgement. The reader should refer to the individual case studies for more specific recommendations that are applicable to that particular infrastructure.

**Moderate Vulnerability** – Based on professional judgement there is a moderate risk of failure of the component from an interaction with the identified climatic factor. Moderate vulnerabilities will require remedial action in the medium-to-longer term and would involve specific actions that are likely lower in scope and cost compared to higher vulnerabilities.

The number of instances where the vulnerability has been identified through the case studies is identified numerically in the table.

The case study results presented in Table 9 lead to the following observations.

- Based on one case study, buildings in Ottawa are demonstrating high vulnerability to changes in snow and wind events.
- Cooling systems may be highly vulnerable to changes in humidity.

**9.2.1 Observations and Conclusions**

Based on these case studies and the input from experts at the Public Infrastructure Engineering Vulnerability Committee Workshop, the following recommendations can be made regarding buildings infrastructure.

Based on past extremes and climatic variation, the most destructive impacts on buildings are the impacts on the structures themselves, including compete destruction during extreme storm events resulting from floods, heavy storms, etc. In addition to the direct impact of weather events on the building envelope it is important to also consider the indirect impact of weather on the natural environment surrounding buildings. Indirect environmental effects may include landslides, flooding, etc.

In the context of climate change, more aggressive climatic conditions will represent additional burdens on buildings and will prompt a greater need for inspection and maintenance. It may require substitution of some construction materials to provide additional durability and reliability under more extreme conditions.

Some responses will be site- and region-specific. Buildings in parts of northern Canada where foundations historically have been constructed on permafrost need special consideration as climatic warming leads to deterioration of permafrost.

For buildings, as other infrastructure, good design and maintenance practices support adaptive capacity to climate change. Furthermore, inadequate records contribute to making buildings more vulnerable to climate change. Data gaps specifically identified and requiring attention relative to building infrastructure are:

- wind loading;
- snow loading; and
- how durability and weathering processes can affect structural resiliency.
Building envelopes may be of higher concern than buildings' mechanical systems, which can be more readily adapted or changed.

Building foundations are a key area of vulnerability, especially in the north. More monitoring of foundations is required, particularly in northern locations.

Given the large number of buildings and differences in design across the country, more studies are needed of buildings infrastructure relative to climate changes.

Vulnerability of buildings to climate changes can alter over time and facilities should be assessed over the course of their full lifecycle.

The north shows signs of more rapid warming than other regions. For this reason, northern permafrost issues should receive early and high priority for vulnerability assessment.

The work on buildings infrastructure's vulnerability to climate changes resulted in the following recommendations:

- Update building codes and guidelines to reflect climate change;
- Conduct more studies of buildings infrastructure to better reflect the large number of buildings and differences in design across the country;
- Address wind loading more fully in future assessments;
- Address snow loading more fully in future assessments;
- Assess the vulnerability of buildings to climate change over the full service life of the facility;
- Conduct more monitoring of building foundations in northern Canada;
- Make permafrost issues in the North an early and high priority focus of ongoing vulnerability assessment; and
- Encourage better understanding of how durability and weathering processes can affect structural resiliency.

10 Conclusions and Recommendations

The conclusions and recommendations that are provided in this report are based on the literature reviews and seven case studies conducted in the four infrastructure categories as well as input from experts at the Public Infrastructure Engineering Vulnerability Committee National Workshop in March 2008. These are preliminary findings based on a limited number of case studies and the opinions of engineers and experts who assessed the work to date. The conclusions require further confirmation through additional work, which is one of the key recommendations for moving beyond this stage of the project.

It is apparent that few, if any, public infrastructure systems function in total isolation. Themes of interdependence and multiple impacts from the same climatic factor surfaced repeatedly during this study. For example, a severe and intense rainstorm that exposes a water or wastewater treatment plant’s vulnerability could also damage roads and power lines serving the treatment facility. This could impede delivery of electricity, service personnel or supplies necessary to return
the treatment plant to regular operation. Similarly, buildings depend upon other infrastructure systems to deliver water and energy, and to remove wastewater. Furthermore, certain buildings are essential for the proper operation and control of water, energy and roadway infrastructure systems and if these are taken out of service the service capacity of the whole system may be compromised.

The work to date has classified high and medium engineering vulnerabilities which are defined as:

**High Vulnerability** – Based on professional judgement (engineering and operational) there is a high risk of reduced or limited performance and perhaps even failure of the element due to the indicated climatic factor. High vulnerabilities will require remedial action in the short-to-medium term. In many cases, the design can accommodate these changes in the operating environment. However, in other cases, vulnerabilities can occur that require review, prioritization and, for this level of vulnerability, are severe enough to require mitigation and/or adaptive strategies to compensate for the vulnerability. These actions may range from retrofitting or rehabilitating the component to changes in operations/maintenance procedures or to more detailed engineering analysis.

A high vulnerability may also exist if there is insufficient information or too many unknowns to make a professional judgement. The reader should refer to the individual case studies for more specific recommendations that are applicable to that particular infrastructure.

**Moderate Vulnerability** – Based on professional judgement there is a moderate risk of failure of the component from an interaction with the identified climatic factor. Moderate vulnerabilities will require remedial action in the medium-to-longer term and would involve specific actions that are likely lower in scope and cost compared to higher vulnerabilities.

It is concluded that these definitions are appropriate descriptors for this level of analysis and should be brought forward as the basis to classify and scale vulnerabilities for future assessments.

Some climate changes lead to common vulnerabilities and responses regardless of the category of infrastructure. These are described in each of the four sections of the infrastructure category.

It was concluded that the impacts of climate change cannot be ignored. Based on the case studies completed to date, these particular infrastructures:

- were designed to withstand extreme events; and
- have sufficient resiliency to accommodate multiple extreme events over the projected service life period provided that:
  - other stressors (population, maintenance practices, age, etc.) affecting infrastructure capacity are appropriately managed; and
  - extreme events do not occur simultaneously or cumulatively over a short period such that the infrastructure system is still recovering from the previous event.

The nature and severity of the vulnerability of the four infrastructure categories to cumulative or simultaneous extremes at the component level requires further assessment. This was a key learning from this work and was not completely addressed in the case studies that have been completed to date.
Additionally, the case studies demonstrated that infrastructure capacity may be consumed by slowly changing climatic norms such as increasing ground temperature in the north or sea level rise in coastal communities. These creeping changes in climatic conditions, when combined with other stressors can result in infrastructure failure and should be more of a focus in future work.

10.1 Conclusions

The conclusions arising from the work completed to date can be categorized into the following seven themes:

1. Some infrastructure components have high engineering vulnerability to climate change.
2. Improved tools are required to guide professional judgment.
3. Infrastructure data gaps are an engineering vulnerability.
4. Improvement is needed for climate data and climate change projections used for engineering vulnerability assessment and design of infrastructure.
5. Improvements are needed in design approaches.
6. Climate change is one factor that diminishes resiliency.

**Theme 1: Some infrastructure components have high engineering vulnerability to climate change.**

In the case studies a number of components that demonstrated high vulnerability to climate change. These are listed below under each infrastructure category. More work is required to confirm the applicability of these conclusions to infrastructures located elsewhere in Canada.

**Water Resources**
- Dam structures and seawalls in these locations may become more vulnerable to flooding.
- Intake structures, on the Prairies in particular, may be vulnerable to drought conditions restricting feed-water supply to potable water treatment facilities.
- Intense winds, particularly tornado conditions, present a risk to variety of infrastructures. In this case the probability of the event was generally determined to be very small. However, the consequence of the event was extreme.
- Ice storm events were determined to create a vulnerability to power supply systems putting the water resources infrastructure at risk.
- In Placentia, the most important risk factor was determined to be a combination of rising sea level and storm surge. At the Public Infrastructure Engineering Vulnerability Committee Workshop, participants agreed that similar risks are being faced by most coastal infrastructure in Canada and recommended that the next series of engineering vulnerability assessments include studies of coastal infrastructure.

**Stormwater and Wastewater**
- In Metro Vancouver, sewer trunks, interceptors and sanitary mains are vulnerable to an increase in intense rain events.
- Common with the Placentia case study, coastal infrastructure is vulnerable to storm surge.
**Roads and Associated Structures**
- On the Quesnell Bridge, ice accretion and freeze-thaw cycles were found to create potentially significant vulnerabilities.
- The most significant vulnerability observed for road systems in Sudbury resulted from a projected increase in heavy snow events. This had an impact on snow removal procedures for sidewalks.

**Buildings**
- Some buildings in Ottawa are demonstrating a high vulnerability to changes in snow and wind events.
- Cooling systems may be highly vulnerable to changes in humidity.

**Theme 2: Improved tools are required to guide professional judgment.**
The Engineering Protocol provided a consistent framework for the engineering vulnerability assessment for the seven case studies in four different infrastructure categories. However, some aspects of engineering vulnerability assessment could not be measured and practitioners were required to make decisions that demanded the application of professional judgement. These aspects included:

- Definition of catastrophic failure varies by type of infrastructure as well as between owners and operators
- Definition of critical loss varies as a function of the infrastructure performance factors used to judge engineering vulnerabilities
- Required levels of service of the infrastructure (would likely be defined for each individual assessment)

The Protocol enables each individual assessment to exercise professional judgment to overcome deficiencies in the availability of climatic and/or infrastructure data and demands that such judgement be documented. However, this documentation was limited by the availability of rigorous definitions that apply to the individual infrastructure categories and/or collectively to all of them.

All infrastructure is critical to someone but certain short-term or localized loss of infrastructure systems may be tolerated. However, longer-term losses causing significant public-safety concerns and major socio-economic impacts (for instance, the 1998 ice storms in Quebec and Ontario) are not acceptable.

Acceptable levels of disruption (level of service) will vary by community, the type of infrastructure and the service it provides. Engineers, political decision-makers, members of the general public, and other stakeholders often have differing definitions of what constitutes infrastructure failure.

Better consensus is needed regarding the definition of what is considered critical loss of infrastructure as well as what constitutes a catastrophic failure. These definitions are needed for each of the four infrastructure categories assessed in this work.
**Theme 3: Infrastructure data gaps are an engineering vulnerability.**

Many of the case studies reported significant gaps in the availability of infrastructure data. Thus engineers, operators and decision-makers have no clear definition of the capacity and resiliency of the system. These data gaps contribute to the overall vulnerability of infrastructure.

The case studies identified a number of examples in infrastructure data gaps, including:

- incomplete or missing maintenance logs and records;
- records based on accounting or cost information without reference to actual maintenance or operational details;
- anecdotal records of increased maintenance activity resulting from extreme climatic events unsupported by written reports;
- missing design information;
- not as apparent on newer systems such as the Portage la Prairie Water Treatment Plant or the City of Edmonton Quesnell Bridge but more apparent in systems that incorporate older infrastructure elements;
- data that is not reflective of actual, in field, systems;
- Missing or incomplete as-built drawings; and
- missing, unmonitored or unsuitably formatted climatic data.

It is likely that such gaps for these infrastructures will be more pervasive in smaller communities that lack the resources to maintain such information. Information may be lacking on existing infrastructures that are well into, or past their service life because of their age and different design standards that were utilized at the time, which increases their engineering vulnerability to climate change. In the absence of such data, infrastructure designers, including engineers, must rely upon professional judgement to determine the engineering vulnerability as well as decisions on the timing and nature of retrofit, rehabilitation or replacement.

Limited documentation, including past maintenance records, was an important factor in some of the case studies. It was not uncommon for certain information to be missing or not available, particularly original design drawings or reports that may be decades old.

To overcome some of these limitations a workshop with system operators and maintenance was a tremendously valuable exercise to supplement existing records or lack thereof.

**Theme 4: Improvement is needed for climate data and climate change projections used for engineering vulnerability assessment and design of infrastructure.**

The seven case studies completed to date have revealed significant gaps in the types and nature of historical climate data needed to conduct engineering vulnerability assessments. The historical data establishes the baseline to compare future changes derived from the climate change projection models.

Based on the case studies completed so far, there were many important climatic factors for which data (and projections) do not exist, unless it was collected locally, which is rare. These include:
**Water Resources**
- Stream flow data under climate scenarios
- Hail
- Frost cycle/change in frost season
- Ice accretion
- Ice buildup
- Compounding or cascading events

**Stormwater and Wastewater Systems**
- Hail
- Frost cycle/change in frost season
- Compounding or cascading events
- Five year – 24 hour rainfall factors

**Roads and Associated Structures**
- Relative humidity
- Models can predict trends but may not give extreme values necessary for design
- Compounding or cascading events

**Buildings**
- Ground temperatures
- Humidity
- Freeze-thaw (perhaps a model to calculate this at local scales)

Similar gaps should be expected for future engineering vulnerability assessments conducted elsewhere in the country. Owners and operators should be encouraged to start systematically collecting this data locally to support future upgrades or rehabilitations of their infrastructures.

Environment Canada does not gather certain weather data relevant to gauging infrastructure vulnerability (e.g., ground temperatures). In other cases, where data is collected, meteorological gathering stations may be spaced too far apart or report too infrequently to provide extreme storm data that would be useful in designing robust infrastructure. There is need for infill environment data from other sources and partners such as municipalities.

The case studies used climate change projections based on the Regional Climate Model operated by Ouranos. The model generates projections of a limited set of climatic factors in a 45 kilometres grid spacing. Based on the work completed to date, it is concluded that the application of these projections for future engineering vulnerability assessment requires engineering judgement based on the following considerations:

- design or service life of the infrastructure (or the estimated timing for future retrofit or rehabilitation);
- many of the climatic parameters are not available so estimates must be used that are based on local measurements or historical data (with judgment around how this might change);
- the regional scale (45 kilometres) of projections does not meet site-specific engineering scales needed for design and engineering vulnerability assessment.
- practitioners conducting engineering vulnerability assessments would benefit from having climate change predictions framed within bands or ranges.
- model projections may be used as an indicator, or “flag” of future changes and applied in “what if” scenarios and/or trend analysis of local historical data (if available).
Trend, threshold and/or sensitivity analysis is needed to supplement results from climate change projections based on models. Generally, engineers need better understanding of, and confidence in, climate models before using them beyond providing an indication of where changes in a given parameter are more likely.

The work undertaken to date has identified a need for enhanced dialogue between the engineering profession, meteorologists and climate scientists (modellers). Often data is being processed in ways that are inconsistent with the needs of the engineering profession. By working together, analyses more suited to meet engineering needs, design and standards development can be produced from existing databases.

In addition, engineers often simply use meteorological and climate data provided to them without a full understanding of the data sensitivity, precision and accuracy. Improved communication between climatologists and engineers is needed to explain what climate models are saying as well as their limitations. This will help engineers make appropriate judgements in the use of this information for engineering vulnerability assessment and design purposes.

**Theme 5: Improvements are needed in design approaches.**

It was the consensus of the participants at the national workshop that significant changes in climate “normals”, in particular rises in average seasonal temperatures in northern Canada, have occurred in recent decades. However, many codes and standards used for infrastructure design date from 1970s and are calculated using less than 30-year averages (a commonly used time frame to establish climate design parameters normals). For example, the temperature data contained in the bridge design standard (Can/CSA-S6-06) should be reviewed and updated since temperature data is based on records up to 1970 and relative humidity isolines are based on 10 years of data form 1957 to 1966.

There is a need to systematically document the climatic data that has been used to establish climatic design values in existing codes and standards in the four infrastructure categories.

Using the Protocol and other tools, it is important during design as well as in subsequent operations and maintenance to consider the entire life of an infrastructure system. However, it is necessary to differentiate between the design life and service life of infrastructure. Some facilities may continue to be used and remain robust long past the end of their design life. Climate change vulnerabilities may arise between the end of the design life and the useful service life.

It is much easier to apply results of an engineering vulnerability assessment during design than to existing, mature facilities. It is important to apply assessment of climate change vulnerability to new technologies many of which have unknown performance capabilities relative to the effects of climate change on infrastructure.
Theme 6: Climate change is one factor that diminishes resiliency.

In recent years, concerns have been raised in Canada about the present levels of maintenance and future needs for infrastructure.

Factors affecting the resiliency of infrastructure may include the age of the asset; level of maintenance and monitoring of facilities; changes in populations; and the amount of use the infrastructure receives. Climate change is likely to intensify the engineering vulnerability if current levels of maintenance continue. Properly maintained infrastructure enables the infrastructure and its components to function as designed, which includes accounting for changing climate events. A holistic approach is needed to deal with the issues, including the coordination of financial, managerial and social factors as well as climate change adaptation.

The case studies revealed that certain infrastructure components are dependent on power – for example, for powering pumps, streetlights, traffic controls, and for heating ventilation and communications. While short-term electrical outages may be acceptable under some circumstances, longer-term disruptions may lead to critical loss of function.

In the opinion of the national workshop participants, infrastructure in smaller municipalities is likely to be more vulnerable to climate changes because smaller communities may not have the economic and human resources necessary to assess and mitigate such impacts. Remote northern communities face added vulnerability because of distance and cost, and also due to particular circumstances in the region (e.g., deteriorating permafrost and more rapid temperature increases).

Theme 7: Engineering vulnerability assessment requires multi-disciplinary teams.

Assessment of vulnerability to climate change requires interdisciplinary approaches involving a range of expertise, including but not limited to engineers, climatologists, architects, hydrologists and others. Ideas on the vulnerability of a piece of infrastructure may differ between engineers and managers, on the one hand, and, on the other, personnel involved in day-to-day hands-on operation of infrastructure.

Given the differing perspectives on what constitutes vulnerability and acceptable levels of risk, it is critical that all vulnerability assessment work draw on the expertise and experience of the entire spectrum of stakeholders and work towards a consensus regarding the resiliency of the overall infrastructure system. What is viewed to be a critical loss of service for one group may be seen as a minor disruption to another. Once again, better consensus regarding the definition of what is considered critical loss of infrastructure is needed.
10.2 Recommendations

Five recommendations arise from the work completed to date:

1. Revise and update the Engineering Vulnerability Assessment Protocol.
2. Conduct further work.
4. Assess the need for changes to standard engineering practice.
5. Initiate an education and outreach program.

Recommendation 1: Revise and update the engineering vulnerability assessment protocol

During the execution of the case studies a number of minor issues were identified with the current version of the Engineering Vulnerability Assessment Protocol (Rev 7.1, 31 Oct 2007). Of seven case studies, three consulting teams encountered some difficulties interpreting of the Protocol requirements.

The clarification should:

- update the Protocol to provide further clarification where practitioners experienced confusion or difficulty interpreting requirements;
- reduce ambiguity in nomenclature and interpretation of definitions;
- clarify the risk assessment approach of the Protocol and provide a brief synopsis of risk assessment fundamentals;
- provide further guidance regarding the application of professional judgement during vulnerability assessments; and
- provide greater emphasis on the requirement to employ a multidisciplinary team of professionals to execute the assessment.

Recommendation 2: Conduct additional work to further characterize the vulnerability of Canadian public infrastructure to climate change

There is a need to conduct further work to more fully characterize the vulnerability of Canadian public infrastructure to climate change. The following factors should be considered in deciding on the scope and location of this work.

- Most of the infrastructure evaluated in the current set of seven case studies, to some extent, demonstrated vulnerability to power supply. This may indicate a need to evaluate power-infrastructure systems as an additional infrastructure category.
- The experts have concluded that coastal infrastructure may be particularly sensitive especially to the combined effects of sea-level rise and storm surge. In particular, they have recommended that consideration be given to conducting engineering vulnerability assessments on port facilities and on airports located at sea level.
- The sampling matrices developed through this process should be used to direct the identification of additional work in the four categories of infrastructure evaluated to date.
- The thermosyphon study, which looked at one infrastructure element in ten separate buildings, may serve as a model for evaluating infrastructure vulnerability over a wide geographic region. Several “standard” assessments may be conducted to identify potential vulnerable infrastructure components. The vulnerability then can be more fully characterize by assessing these particular components in a statistically relevant number of systems across the region.
• Future engineering vulnerability assessments should also consider climate events that initiate a sequence of events that may affect infrastructure. The seven case studies conducted for this report did not focus on events, external to the infrastructure, that may have adverse impacts on the infrastructure. This was occasionally identified in the form of potential cascading events, but was not the primary focus of the case studies. Future assessments should broaden their scope to systematically address these potential impacts. To clarify, examples may include:
  • Landslide from severe rain events interrupting road service; and
  • Upstream events affect the operation of a dam that result in higher loading on a bridge structure.
  • Recognize that the resources available for vulnerability assessments will vary depending upon the location and the size of communities.
  • Acknowledge that vulnerability of infrastructure may be more acute in some parts of Canada where rapid and noticeable changes already are occurring (e.g., the North).

**Recommendation 3: Develop an electronic database of infrastructure vulnerability assessment results**

The analysis provided in this report is based on analyzing limited data. As more information accumulates, an electronic database will significantly aid in the analysis of vulnerability trends within a category of infrastructure, regionally and/or nationally.

**Recommendation 4: Assess the need for changes to standard engineering practices to account for adaptation to climate change**

Some of the case studies observed that the current design codes and practices applicable to the infrastructure under consideration could be improved. In some cases, this was related to dated information used within a standard and in others it was based on the view that climate change should be factored into new designs. In light of this experience, further work is need to:

- review codes and standards applicable to the four categories of infrastructure that are the current focus of the Vulnerability Committee and determine specifically where dated climatic information is used;
- maintain a dialogue between engineers, scientists, modellers and climatologists to clarify the climate data needs and formats to support the design and management of engineering;
- maintain a dialogue with codes and standards organizations to communicate the outcomes from this engineering vulnerability assessment in order to evaluate the need to update codes and standards; and
- investigate incorporating the use of the Engineering Protocol for Climate Change Infrastructure Engineering Vulnerability Assessment, or similar assessment processes, into design processes for new infrastructure and major infrastructure rehabilitation in Canada.
Recommendation 5: **Initiate an Education and Outreach Program to Share Learnings from This Assessment with Practitioners and Decision-makers**

Public infrastructure systems do not function in total isolation. Multiple stakeholders have a role to play in ensuring robust and resilient public infrastructure for assurance of serviceability and public safety. Key learning from this initiative should be shared with other constituencies in order to promote effective infrastructure design, operation and management.

Outreach and communication initiatives should:

- communicate the work completed to date to government agencies and policy makers as well as the engineering community;
- heighten awareness of these issues within the engineering community, among facility operators, other professionals, constituent engineers, educational institutions, the public and decision-makers; and
- encourage infrastructure owners and operators to maintain relevant data as part of good engineering and asset management practices, recognizing that:
  - documentation, including past maintenance records, serve as important tools for assessing climate change vulnerability; and
  - historic data establishes a performance baseline necessary to assess infrastructure vulnerability.